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# REPORT

## SOLID POLYMER ELECTROLYTE (SPE) FUEL CELL TECHNOLOGY PROGRAM

### FINAL REPORT (PHASE III)

Contract NAS 9-15286, DRL Line Item No. 4

Prepared for

National Aeronautics and Space Administration  
Lyndon B. Johnson Space Center  
Houston, Texas 77058

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GENERAL  ELECTRIC

## ACKNOWLEDGMENTS

This report summarizes the results of a Solid Polymer Electrolyte fuel cell technology program conducted for the National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, by the General Electric Company, Direct Energy Conversion Programs, Wilmington, Massachusetts, under Contract NAS 9-15286. The period of performance was February, 1977 through January, 1978.

This work was performed under the guidance of Mr. G. D. Hydrick, Jr., Program Manager for the Power and Propulsion Branch of NASA/Lyndon B. Johnson Space Center. The overall program was directed by J. F. McElroy, Project Engineer, General Electric Company, Direct Energy Conversion Programs.



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## 1.0 SUMMARY

The primary objective of Phase III of the Solid Polymer Electrolyte Technology Program was to consolidate the many previously demonstrated improved fuel cell features. The thrust of this consolidation was:

- To obtain a better understanding of the observed characteristics of the operating laboratory-sized cells.
- To evaluate appropriate improved fuel cell features in 0.7 Ft<sup>2</sup> cell hardware.
- To conduct a study of the resultant fuel cell capability and determine its impact on various potential fuel cell space missions.

During Phase III, the observed performance characteristics of the fuel cell at high temperatures and high current densities were matched with a theoretical model. This model shown on Figure 1, is based on the change in Gibbs free energy voltage with respect to temperature and internal resistance change with current density. Excellent agreement between the observed and model performance was obtained.

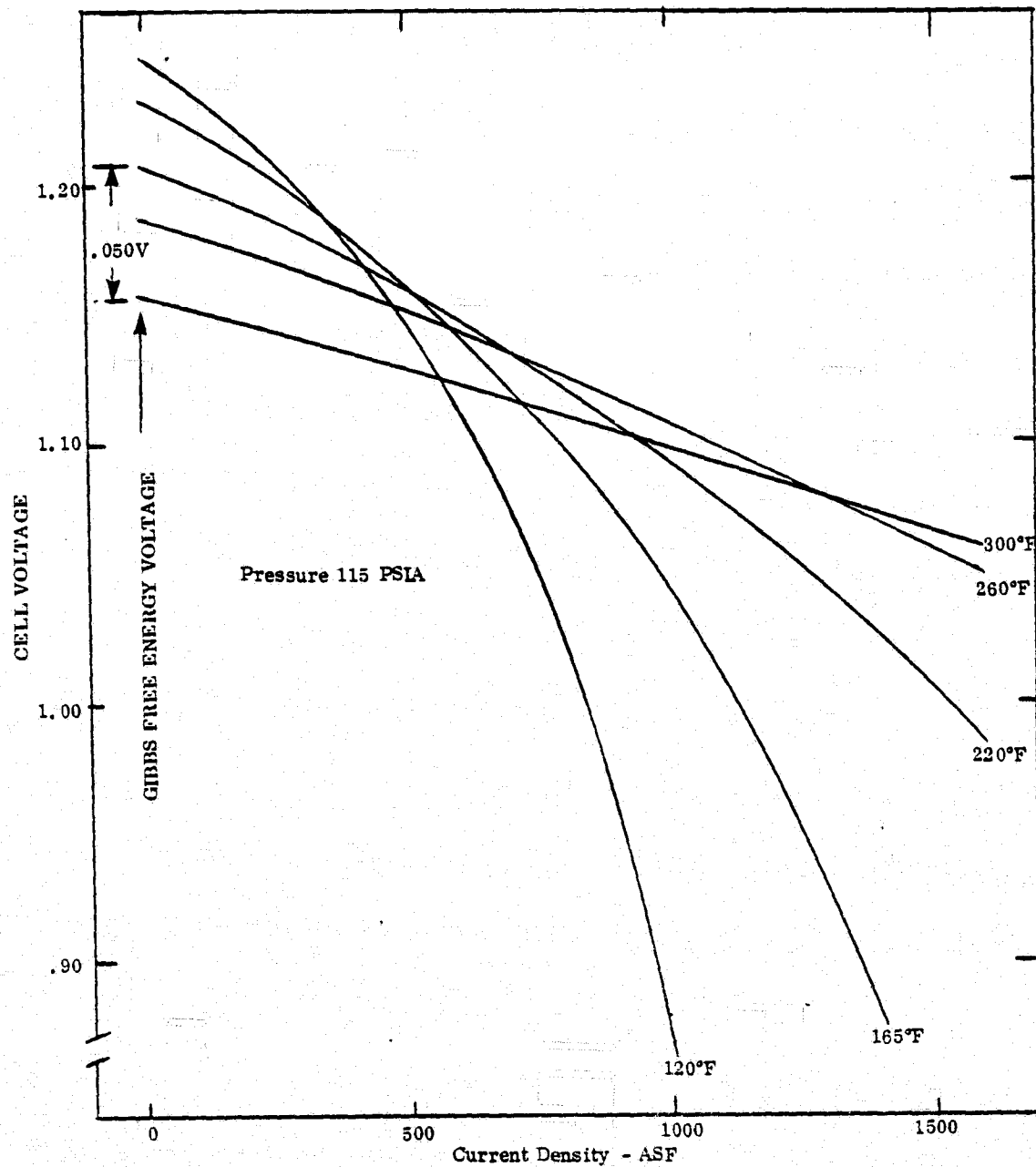
The observed performance decay with operational time on cells with very low noble metal loadings (0.05 mg/cm<sup>2</sup>) were shown to be related to loss in surface area. Cells with the baseline amount of noble catalyst electrode loading (i. e., 4 mg/cm<sup>2</sup>) have demonstrated over 40,000 hours of stable performance. Since the cost incentive for reducing the catalyst loading below the baseline amount for space fuel cell hardware is of minor importance, this effort was discontinued.

In this area of new and modified Solid Polymer Electrolytes some preliminary results indicated that superior levels of performance may be obtainable. Figure 2 displays this potential improvement. Additional effort is planned for early in the Phase IV program.

Several observed occasions were encountered of improved cell performance following operation of the cathode with air as the source of oxidant. A hypothesis of water entrapment within the wetproofing film or between the film and the electrolyte was tested with inconclusive results. Additional effort is planned for Phase IV.

The subscale endurance test task met with several facility malfunctions. Damage to many cells occurred through pressure reversals. A new baseline configuration was established utilizing GE/IR and D developed conductive wetproofing film with electrolyte mechanical support in both reactant





COMPUTER MODEL

PREDICTED IDEAL PERFORMANCE VS. CELL OPERATING TEMPERATURE

Figure 1



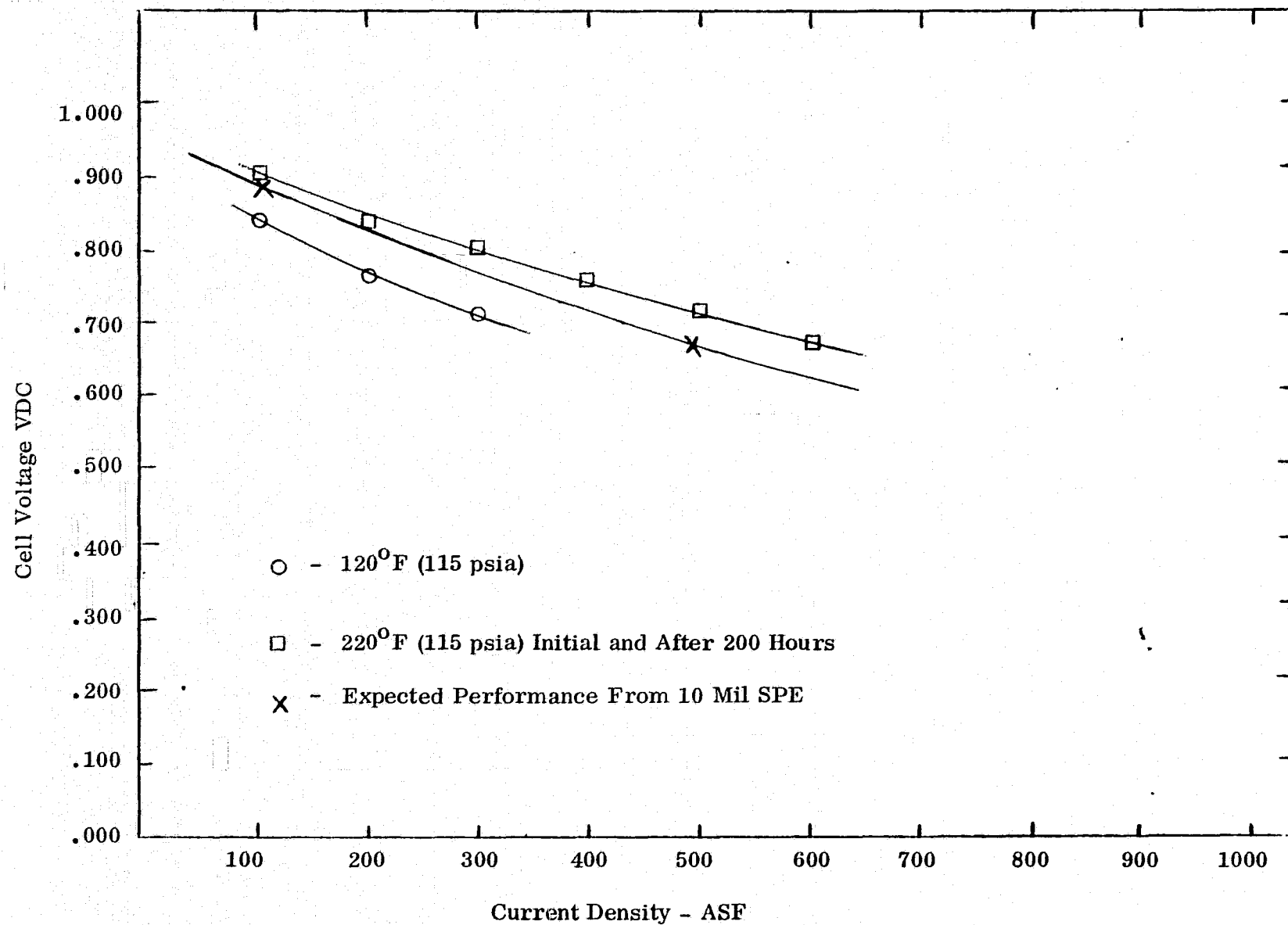


Figure 2. Cell NT (III) 1.4-3 (Platinized Modified Membrane)



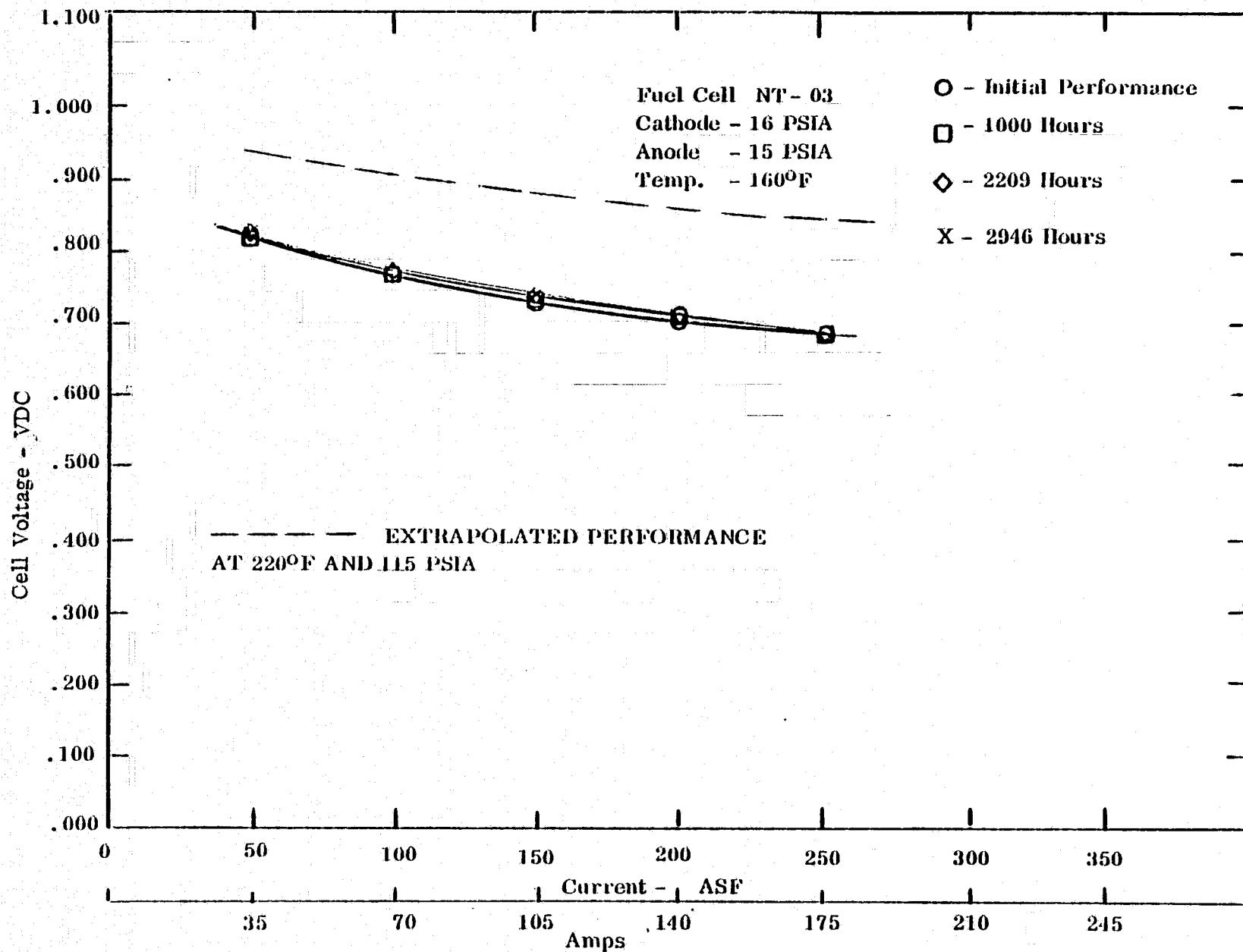
chambers. This arrangement demonstrated considerably improved tolerance to off-design operating conditions. Subscale hardware endurance is planned for a continuing effort.

The 0.7 Ft<sup>2</sup> cell unit (NT-02) had operated for 1672 hours at the beginning of Phase III. Additional hours were accumulated during Phase III up to a total of 3076 hours. At this point, design improvements and advancements were introduced into the hardware and the unit redesignated NT-03. Figure 3 displays the performance data collected over the 3388 hours accumulated on NT-03 by the end of Phase III. The accumulation of additional endurance hours will be performed as part of the GE IR and D Program.

System studies of the potential space applications to which the Solid Polymer Electrolyte fuel cell might be utilized were initiated during the Phase III effort. A preliminary cell sizing of 1.1 Ft<sup>2</sup> active area was selected as meeting many of the requirements of the various applications. Figure 4 displays the concept of the 1.1 Ft<sup>2</sup> hardware. The actual design development of this concept will be accomplished in Phase IV.

The continued NASA support combined with the related technology developments at GE/DECP assures the availability of a low cost/long life/high power density fuel cell technology for future NASA projects. A reactor stack demonstration should be completed within a two-year time frame.



Figure 3 O<sub>2</sub>/H<sub>2</sub> Performance



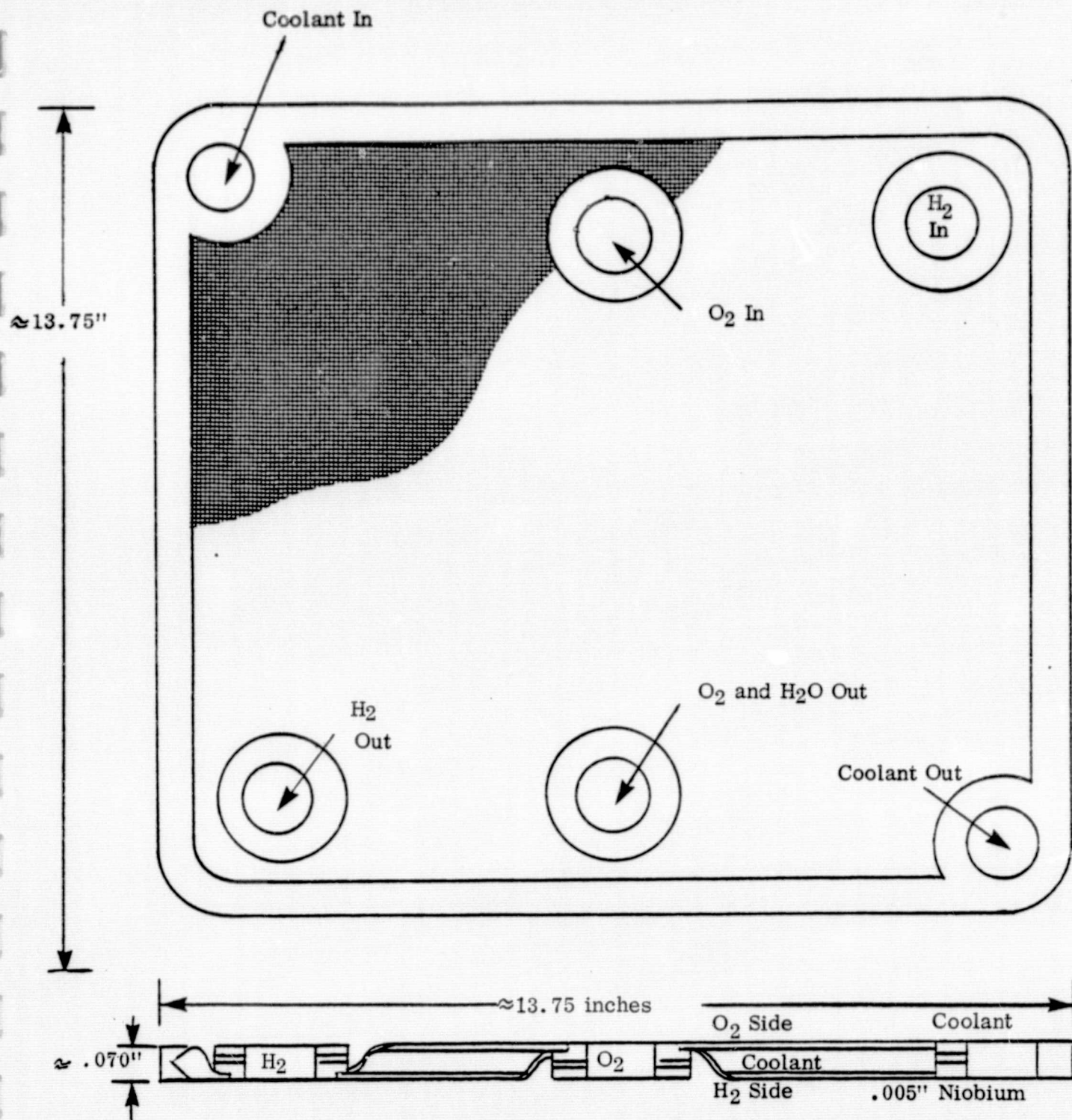


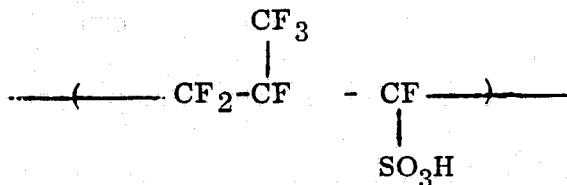
Figure 4 Cell Fluid Separator Assembly (Active Area - 1.10 Ft<sup>2</sup>)

## 2.0 TECHNICAL BACKGROUND

### 2.1 General Background

The SPE fuel cell technology was first developed into a viable product in 1960. Over the past 17 years, improvements in both the SPE and the electrode technologies resulted in an increased field of applications to include electrolysis systems, oxygen concentrators and regenerative fuel cells. All four electrochemical devices utilize the same basic SPE and electrode components. Thus, the experience gained from one application can be used in the further improvement of the other devices.

The heart of these devices is the SPE which is approximately a 10 mil thick plastic film fabricated from ion exchange material. This currently utilized material has a structure as follows:



This is essentially a sulfonated analog of Teflon with physical properties very similar to Teflon.

The use of the SPE as the sole electrolyte in an electrochemical system offers the following advantages:

- Minimum weight
- Immobile and invariant during life
- Minimum volume
- Ease of handling during assembly
- Capability of handling high pressure differentials across the membrane
- No tendency to react with  $\text{CO}_2$  to form carbonates

#### 2.1.1 Solid Polymer Electrolyte Technology

The Nafion<sup>®</sup> SPE described above is a product of duPont and has been utilized extensively by GE/DECP in electrochemical applications since 1968. This membrane is extremely stable, both physically and chemically, while exhibiting excellent physical and electrochemical properties. These properties are listed below:



Property	Value
Tensile	> 2500 psi (>17,235 kN/m <sup>2</sup> )
Elongation	> 120%
Burst Strength, unsupported	> 100 psig (> 689 kN/m <sup>2</sup> gauge)
Water Content	25-40 Weight %
Resistivity	> 15 ohm-cm
Life in Electrochemical System (hours)	> 48,000 hours demonstrated to date in fuel cells.
Thermal Stability	> 300°F (>149°C)

The Nafion<sup>®</sup> SPE is the latest in a series of GE/DECP membrane systems that included phenol-formaldehyde sulfonic, polystyrene sulfonic, and trifluorostyrene sulfonic acids. The Nafion<sup>®</sup> SPE was the only membrane that offered the excellent combination of physical and chemical stability required in the electrochemical environments.

The first Nafion<sup>®</sup> SPE's tended to degrade slowly in an electrochemical environment as evidenced by a slow generation of HF and CO<sub>2</sub> from the operating device. However, this problem has been rigorously researched by both duPont and GE/DECP and has culminated in a stack of 0.38 Ft<sup>2</sup> (354 cm<sup>2</sup>) cells that has been operating over 48,000 hours with a projected life of over 100,000 hours. The performance characteristic over its life to date is shown in Figure 5. It is operating at 70 psia (483 kN/m<sup>2</sup>) oxygen-side pressure and has been run at 180°F for over 37,000 hours with current densities up to 260 ASF (.28 amps/cm<sup>2</sup>).

#### 2.1.2 Electrode Technology

The GE/DECP electrode structures are thin catalyst layers pressed onto the SPE surface. The catalyst/SPE electrode also contains a thin (3-4 mil) (.0762-.1016 mm) current collector screen, and in order to prevent water masking of the fuel cell oxygen electrode where product water is formed, a wetproofing film is placed on top of the catalyst/current collector. The performance of these electrode structures has been invariant for over 48,000 hours with no evidence of performance decay.



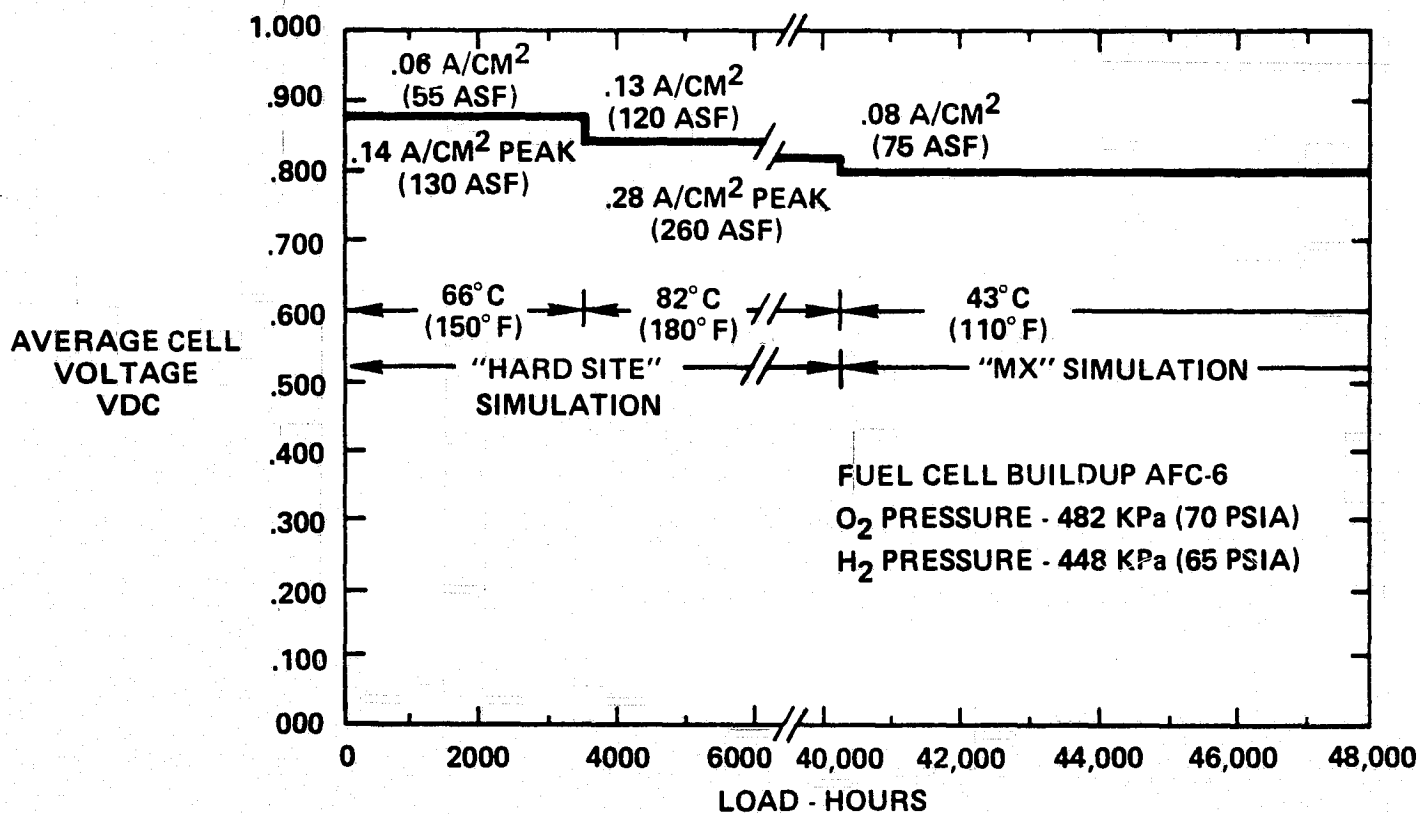


Figure 5

Average Cell Voltage vs. Load Hours AFC-6



## 2.2 Major Fuel Cell Programs

The Gemini spacecraft program marked the first operational use of an SPE unit. The General Electric Solid Polymer Electrolyte fuel cells used on that program successfully completed all seven spacecraft missions, accumulating a total of 850 hours (5000 stack-hours) of flight operation with an excellent record of performance and reliability. The spacecraft system included two 1-KW modules, each containing three 32-cell stacks.

A total of 250 stacks of the production configuration were built during the Gemini program. Most of these were used for reliability, endurance, and over-stress testing and accumulated more than 80,000 stack-hours of operating experience in addition to flight operation.

A second-generation model of this fuel cell design successfully operated in orbit continuously for over 40 days (planned mission of 30 days) on Biosatellite Spacecraft 501 and stopped functioning only when the reactants were depleted.

The so-called "back-to-back" cell design concept, where cathodes of adjacent cells faced each other, was initially developed for Air Force satellites. This concept was continued under NASA's sponsorship.

In this NASA Space Shuttle Technology Development Program, General Electric fabricated and evaluated flightweight fuel cell hardware. Noteworthy is the fact that a 3-cell assembly completed over 6500 hours of life testing, a 38-cell stack accumulated 5000 hours, and a 32-cell stack with ancillary components in a prototype flight configuration achieved 2000 hours of operation.

The technology developed during the Space Shuttle technology has recently been repackaged as a 3 KW fuel cell for the Navy's High Altitude Super-Pressurized Powered Aerostat (HASPA).

Recently under sponsorship of NASA's Lewis Research Center, initial development of a new SPE concept was started. The major feature of this concept was the removal of product water via a dynamic recycling oxygen system as opposed to the traditional wick and separator approach used since the Gemini Program. The advantages of this concept are in the areas of weight, cost and efficiency.

Figures 6 through 8 display the various products described above. Figure 9 is a graphical presentation of the past 15 years of progress in the SPE fuel cell technology.





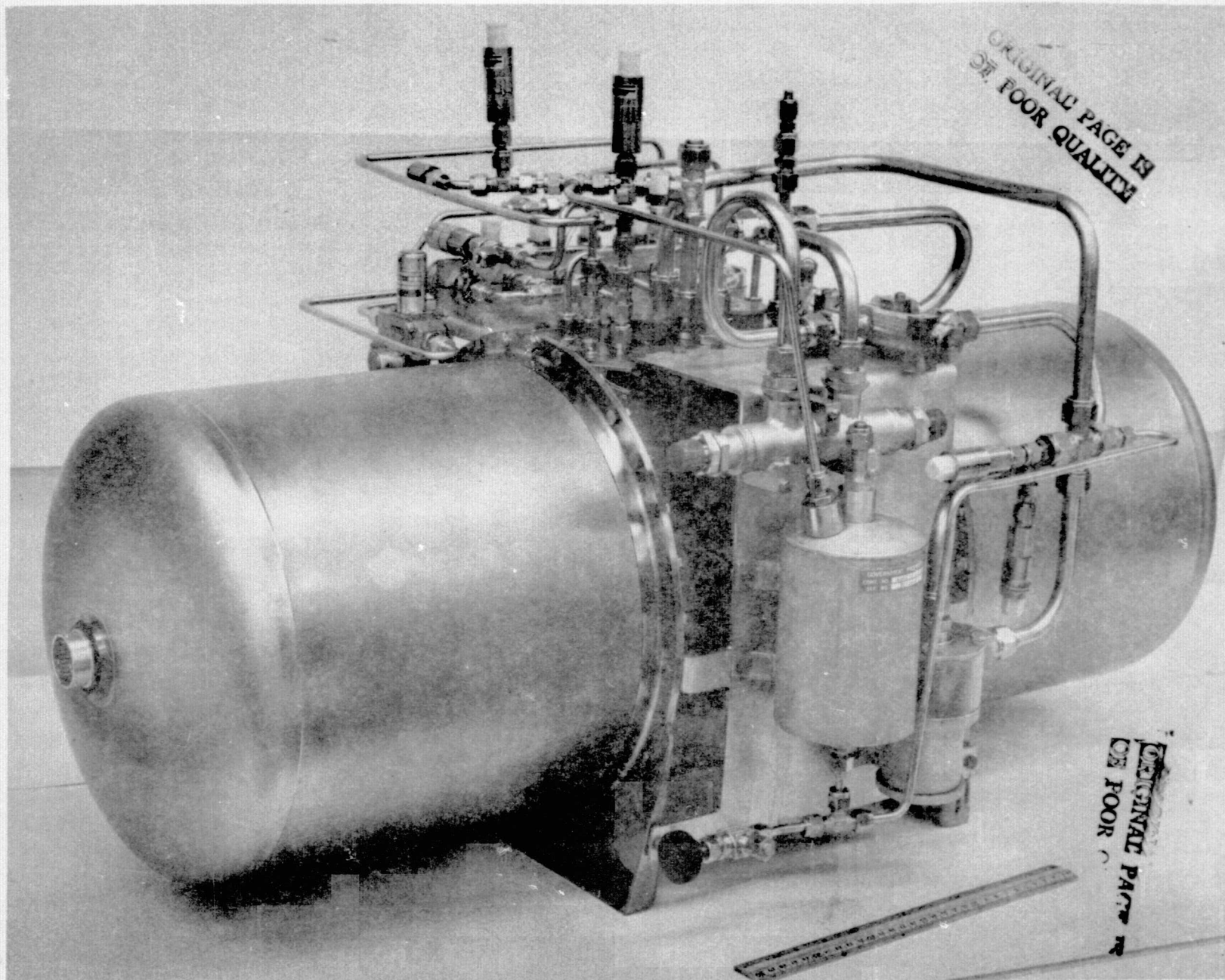
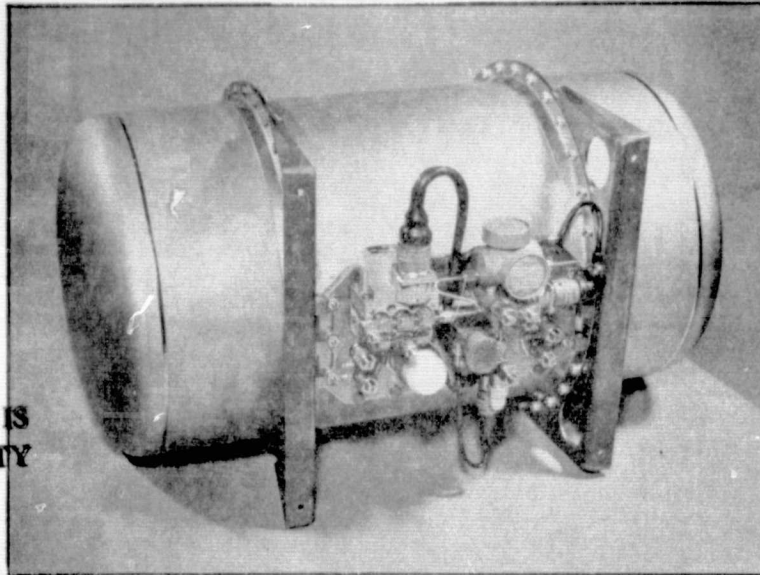
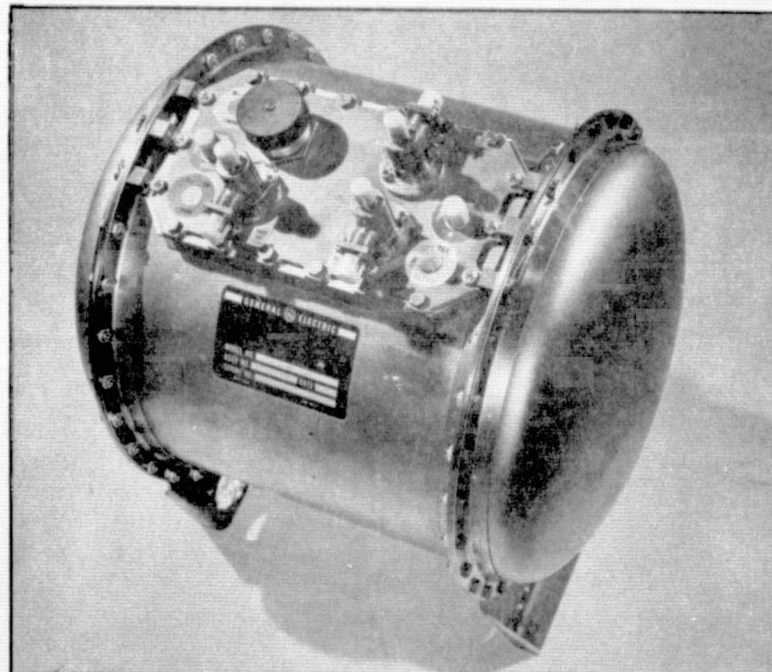


Figure 6. 5 KW Fuel Cell Module with Ancillary Components (NASA/JSC)

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One KW Fuel Cell Module for Gemini Spacecraft



350-Watt Fuel Cell Module for Biosatellite Spacecraft

Figure 6A

12



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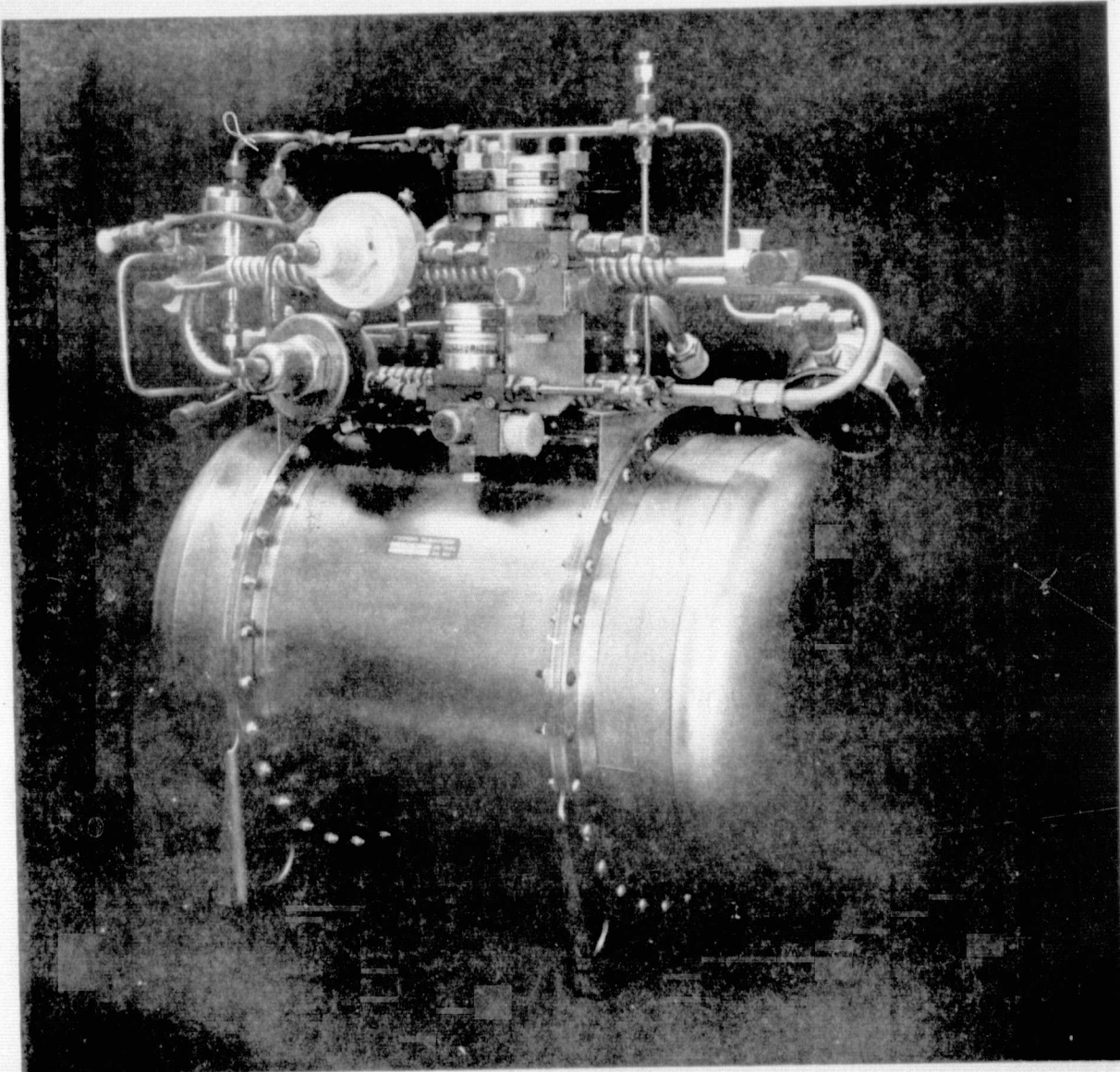
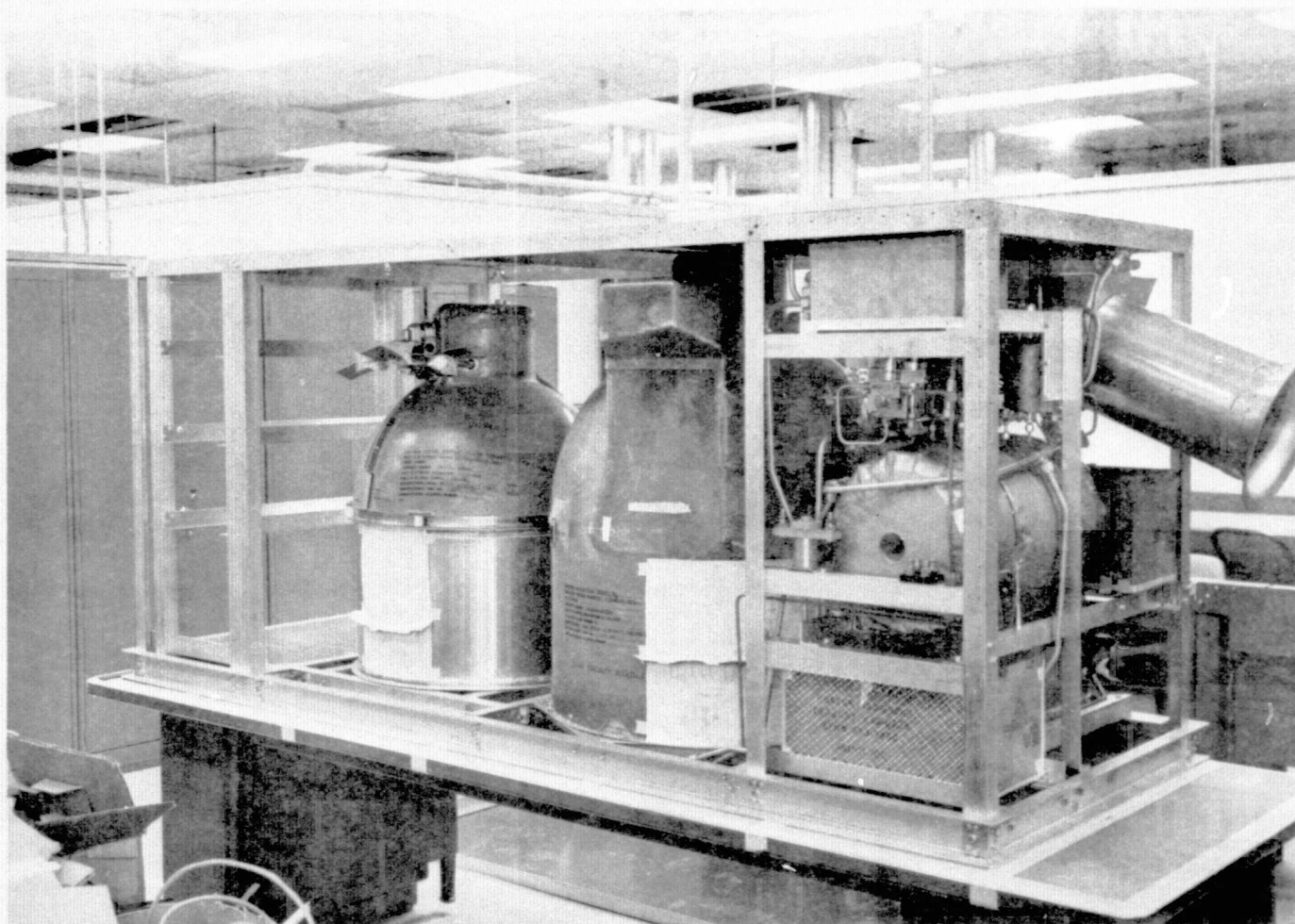


Figure 7. 3 KW HASPA Fuel Cell Module







Complete Fuel Cell Power System, Including Cryogenic Tanks, in the Process of Assembly for U. S. Navy Balloon Program.

The Fuel Cell Performance Remains at Specification Levels Following 1000 Hours Operation and 2 Years Storage.

Figure 8

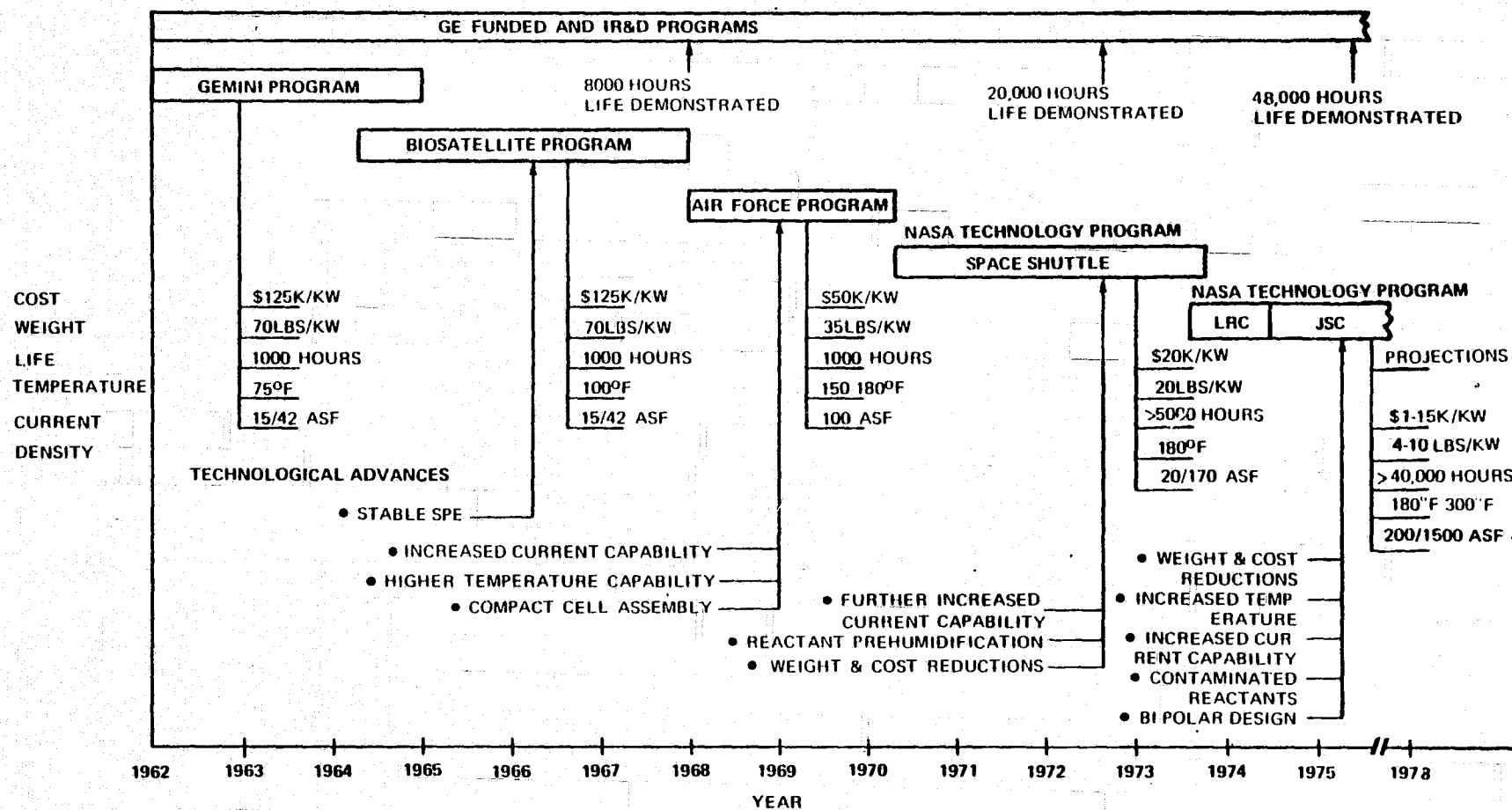


Figure 9. Progress of SPE Fuel Cell Technology

### 3.0 TECHNOLOGY ACTIVITIES

The major tasks of this Phase III Program were directed toward the consolidation of previous technology efforts by:

- Obtaining better understanding of observed performance.
- Demonstrating ability to scale up.
- Selecting appropriate size of hardware for potential future space hardware.

Figure 10 shows the overall Phase III Program Milestones.

#### 3.1 Laboratory Evaluations

This major task was subdivided into two major sub-tasks as follows:

1. Configurations analysis
2. Endurance evaluations

In order to characterize the performance of any given cell, a base line configuration was established utilizing the 1977 state-of-the-art. This base line configuration is displayed on Table I with performance levels as shown on Figures 11 and 12. The performance shown on Figure 11 will be utilized throughout this report to be compared with the performance of the new configuration variations.

##### 3.1.1 Configurations Analysis

The configurations analysis sub-task was divided into five analysis elements. Each of these elements involved observed characteristics from earlier program phases for which a better understanding was desired.

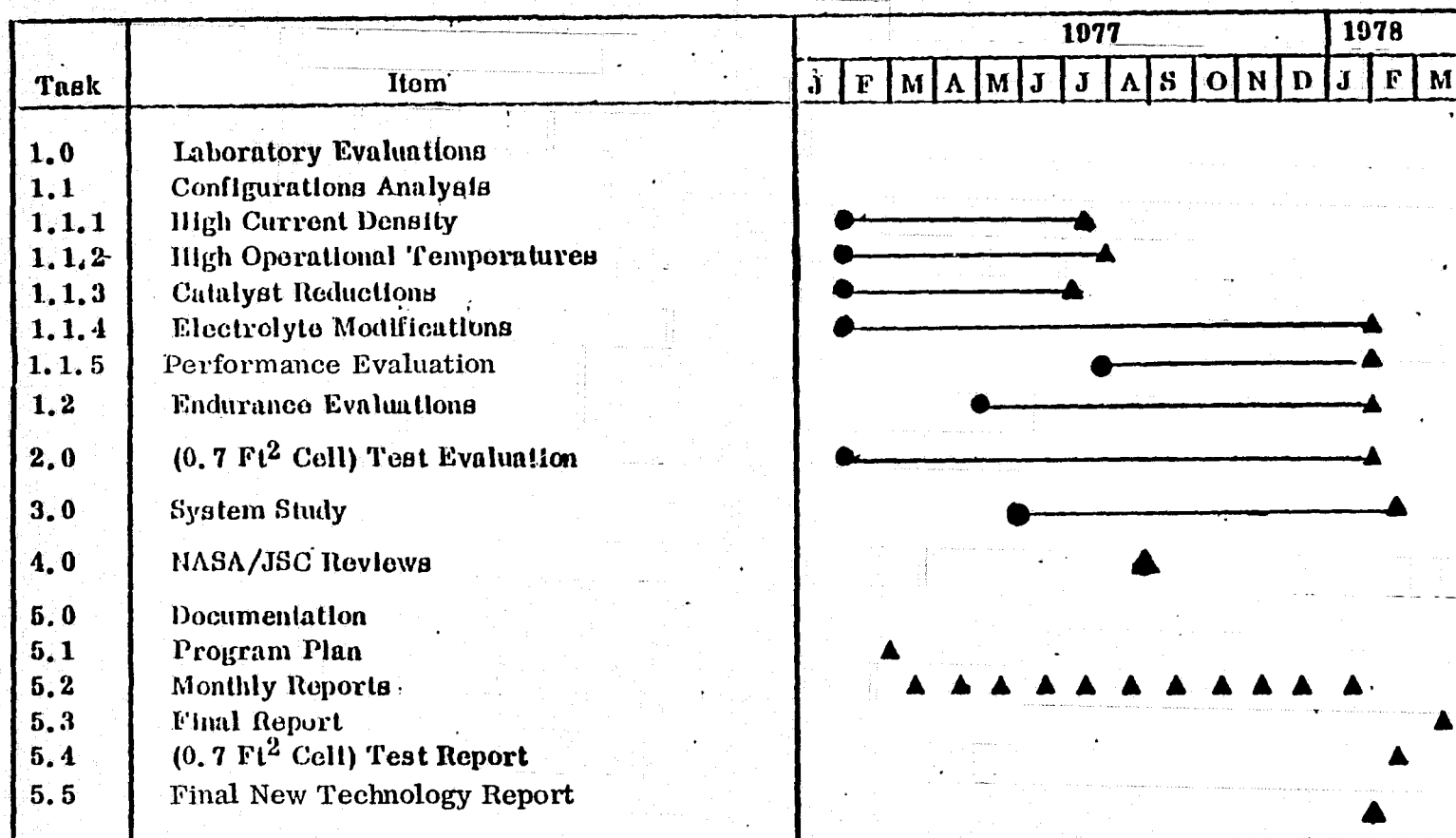
###### 3.1.1.1 High Current Density

During the test evaluations of Phase II a downward bend in the polarization curve of base line cells was observed at current densities greater than 1000 ASF. Also observed during these runs were occasional evidence of water slugs entering the anode cavity from slightly excess humidification. A possible relationship between the downward bend and the excess water slugs was suggested.

An anode trap modification was incorporated into the test hardware which prevented excess liquid water from entering the cell active area. This modification was found in fact to eliminate the water slug problem. However, the downward bend in polarization persisted. A total of five cells were fabricated and evaluated under this sub-tasks element as indicated on Table II. Figure 13 displays the polarization curve for Cell NT(III) 1.1.4 indicating this bend in the



# MILESTONE CHART



\* Contract Modification #1

Figure 10. NASA/JSC TECHNOLOGY PROGRAM PHASE III



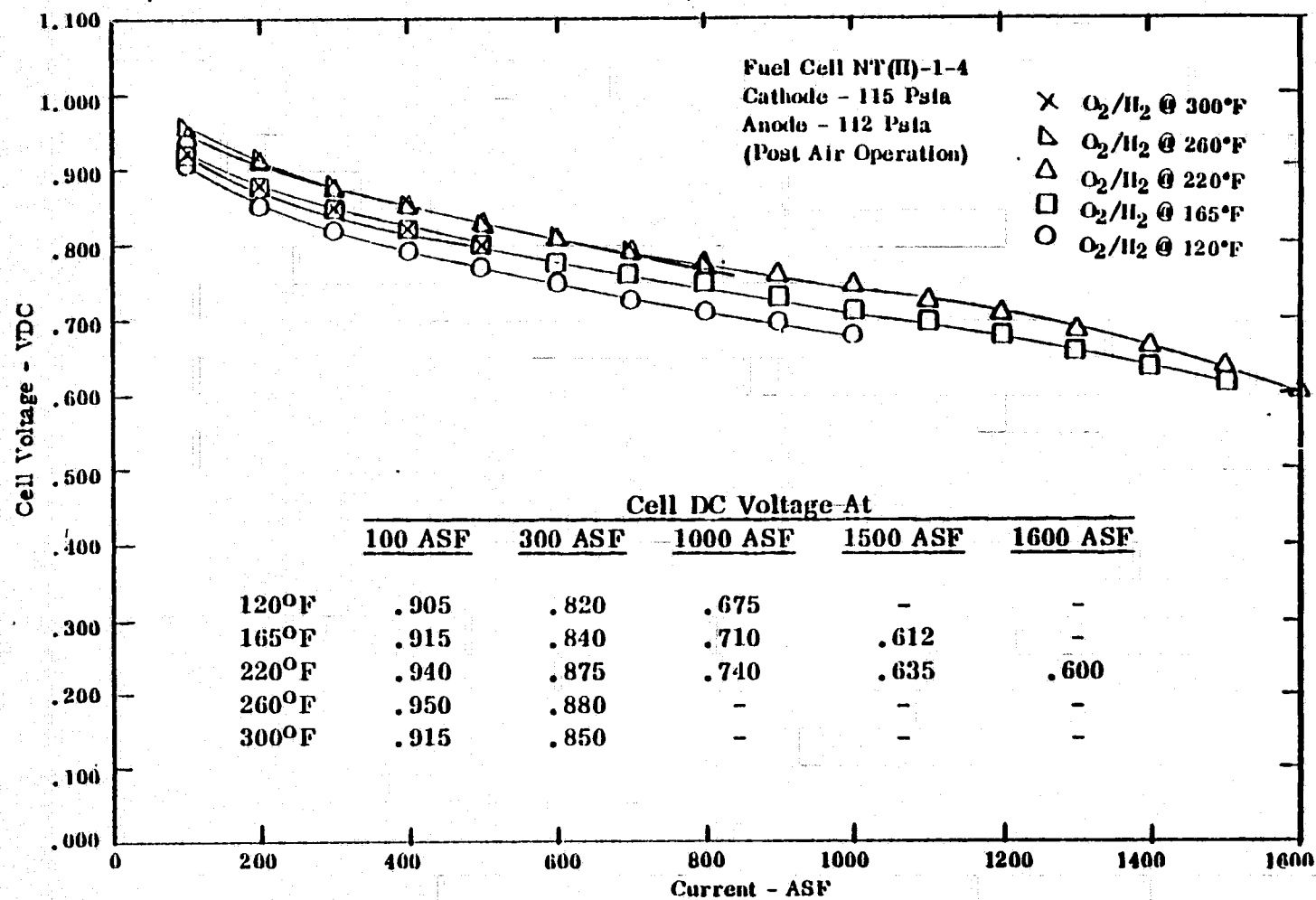
## TABLE I

### SPE CELL CONFIGURATION

A SUMMARY OF THE 1977 BASELINE CELL CONFIGURATION IS AS FOLLOWS:

- SOLID POLYMER ELECTROLYTE
  - DU PONT'S NAFION ®
  - 5 MILS THICK
  - 35-40% H<sub>2</sub>O
  - 1200 EQUIVALENT WEIGHT
  - PLATINIZED
- ANODE
  - 4 GRAMS/FT<sup>2</sup> NOBLE METAL LOADING
  - 64% PT, 21% RU, 15% WO<sub>2</sub>
  - 15% T-42 (TEFLON)
  - GOLD SCREEN (DISTRIBUTION) ASSEMBLY
- CATHODE
  - 4 GRAMS/FT<sup>2</sup> NOBLE METAL LOADING
  - 12.5% T-30 100% PT (TEFLON)
  - 1/4 INCH STAND PIPE
  - 3 MIL GOLD SCREEN
  - CHEMPLAST WETPROOFING (POROUS TEFLON)
- CURRENT COLLECTION
  - BIPOLAR
  - OPEN CATHODE GAP



Figure 11.  $O_2/H_2$  - High Current Density Performance

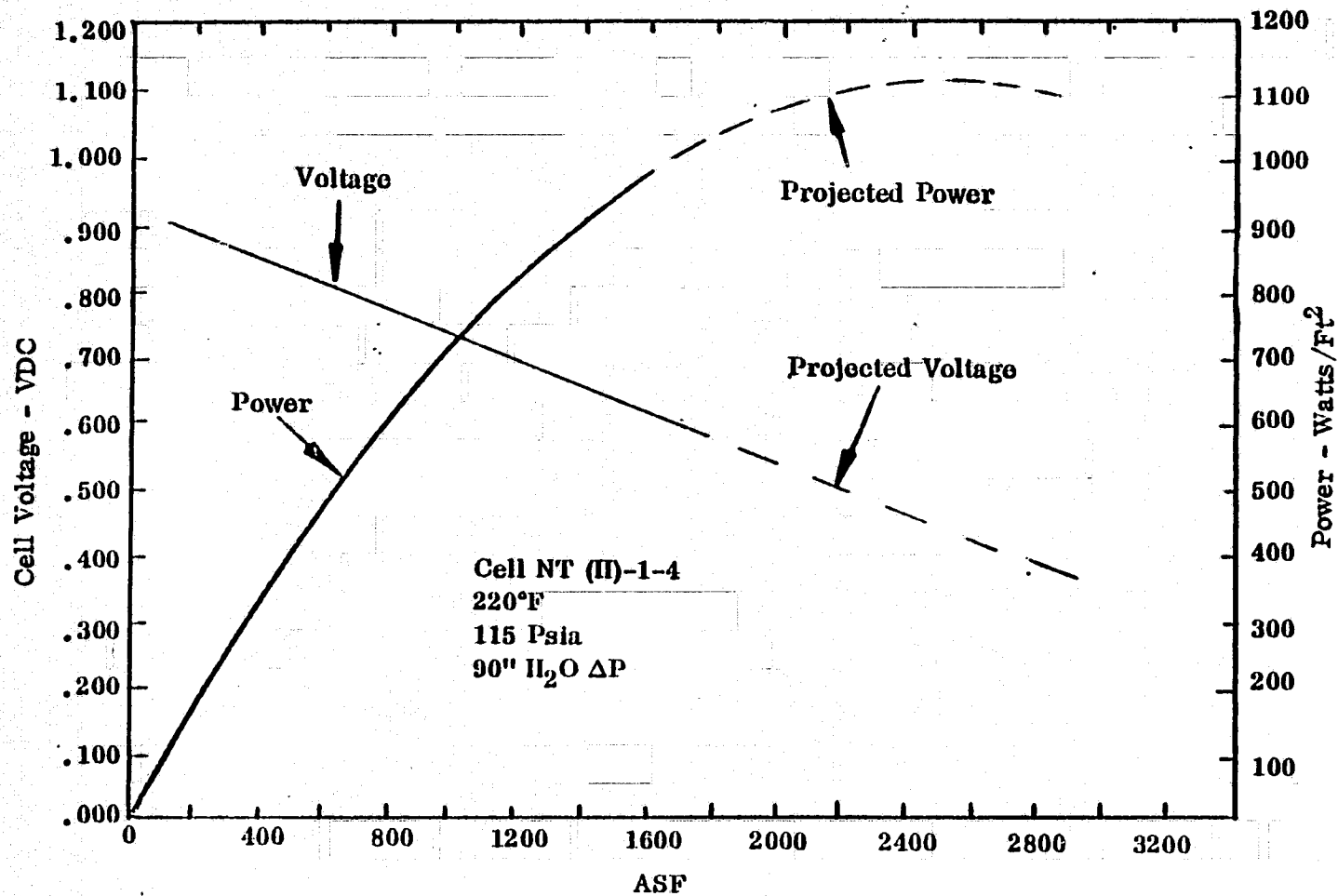
Figure 12.O<sub>2</sub>/H<sub>2</sub> - Power vs. Voltage

TABLE II

TASK 1.1.1 HIGH CURRENT DENSITY

115 psia - Cathode  
112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F .905 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F .820 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F .675 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F .940 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F .675 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .740 VDC	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F .635 VDC	O <sub>2</sub> /H <sub>2</sub> 1600 ASF 220°F .600 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F .915 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F .850 VDC
NT(III)-1.1-1	100% Pt Black Anode	-.018	-.036	-.165	-.021	-.046	-.164	--			
NT(III)-1.1-2	100% Pt Black Anode										
NT(III)-1.1-3	100% Pt Black Anode	-.024	-.052		-.039	-.050					
NT(III)-1.1-4	100% Pt Black Anode	-.036	-.036		-.015	-.025	-.061				
NT(III)-1.1-5	100% Pt Black Anode	-.023	-.042	-.136	-.041	-.065					



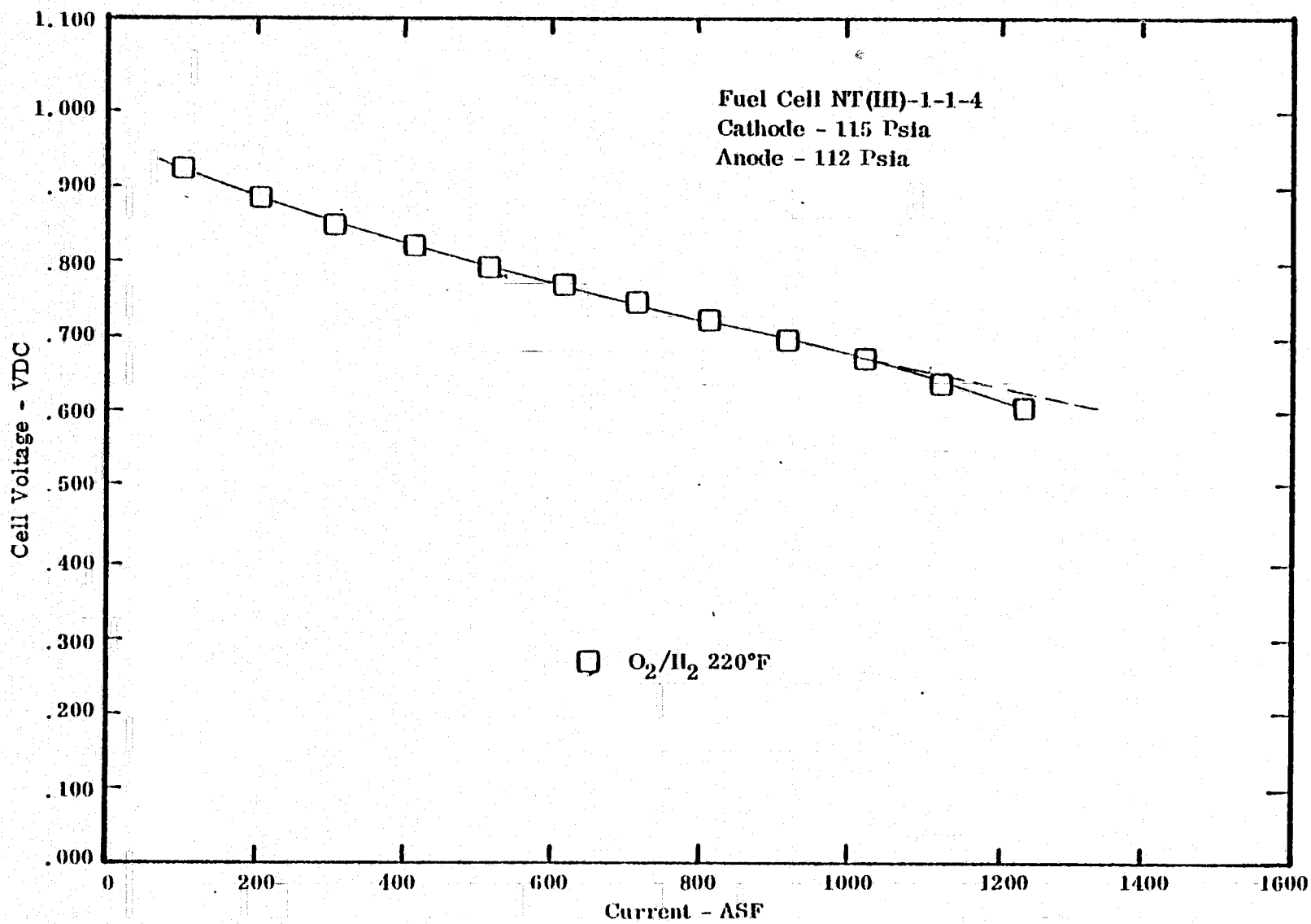


Figure 13.  $O_2/H_2$  Performance vs. Temperature



polarization curve. It was, therefore, concluded that the shape of the polarization of the base line cell was inherent to the cell configuration and not the test hardware.

In order to obtain more insight into the mechanism of this downward polarization bend a model was established as shown pictorially on Figure 14. Mass transport through the polymer was considered to be a likely candidate to influence high current density performance. Well established input data covering "Proton Pumping," water diffusion, and resistance and water content relationships were computer analyzed.

Table III displays the variation in Solid Polymer Electrolyte water content through the thickness of the electrolyte as a function of operating current density. Note the large reduction in water content at the hydrogen side surface with increased current density. This is primarily the result of the proton "pumping" mechanism of the operating cell.

Of course, when water content is lowered internal resistance increases. Table IV displays the expected increase in resistance by this increase in water gradient. Note also the decrease in equivalent ASF loss through diffusion (i. e., lower diffusion with lower water content).

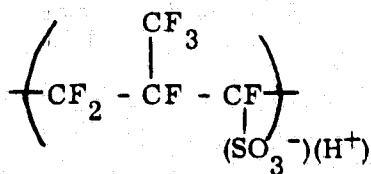
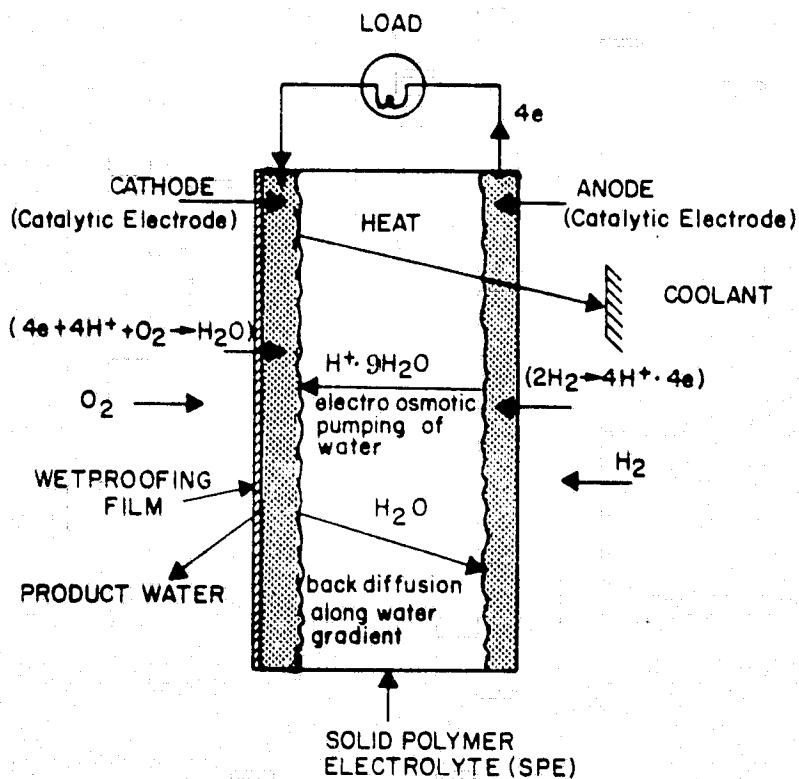
Figure 15 is a plot of the ideal performance (no electrode losses) for a cell with a constant resistance vs a cell with the resistance relative to water gradient as provided on Table IV. It is obvious from this curve that the downward bend should be expected from any increase in current density. However, the small deviations that result at the lower current densities are probably undetected as they are washed out by electrode heating and other small effects. At the higher current densities the effect is greater and considerably more obvious. Figure 16 shows the downward bend of the base line cell with 0.040 volt deviation from 1000 to 1500 ASF. That deviation is in very good agreement with the predicted deviation of 0.044 volt between 1000 and 1500 ASF.

With the close relationship between the model and the operating cell established, it was judged that SPE water gradients result in the observed performance. To minimize the gradients several actions could be taken:

- Reduce SPE thickness
- Increase SPE water contact
- Introduce liquid water into the anode

To reduce the SPE thickness will result in decreased mechanical strength and lower reliability may result.





TYPICAL SPE FUEL CELL CROSS SECTION

Figure 14.

TABLE III

## CHARACTERISTICS OF A FUEL CELL USING A SPE

SPE THICKNESS	.00500 IN.
ION EXCHANGE CAPACITY(IEC)	.82500 MEQ/GM
EQUILIBRATION TEMPERATURE	220 DEG F
EQUILIBRIUM WATER CONTENT	.29805 GM/GM SPE
	.37581 CC/CC SPE
MINIMUM PERMISSIBLE WATER CONTENT	.04335 GM/GM SPE
	.08052 CC/CC SPE
SPE RESISTIVITY(ZERO CURRENT)	12.09898 MOHM-SQ IN.

PRESSURE, PSIA		
HYDROGEN	OXYGEN	WATER VAPOR
112	115	17.18797

CURR DEN	O2 SIDE			H2 SIDE		
100	.2981	.2860	.2743	.2636	.2540	.2456
200	.2981	.2742	.2540	.2380	.2251	.2142
300	.2981	.2634	.2379	.2194	.2048	.1928
400	.2981	.2537	.2248	.2047	.1891	.1763
500	.2981	.2450	.2139	.1926	.1762	.1627
600	.2981	.2373	.2044	.1822	.1651	.1511
700	.2981	.2303	.1961	.1730	.1554	.1410
800	.2981	.2240	.1885	.1648	.1467	.1320
900	.2981	.2181	.1817	.1574	.1389	.1239
1000	.2981	.2127	.1754	.1506	.1318	.1166
1100	.2981	.2077	.1696	.1444	.1253	.1099
1200	.2981	.2030	.1642	.1385	.1192	.1038
1300	.2981	.1985	.1591	.1331	.1136	.0982
1400	.2981	.1943	.1543	.1280	.1084	.0930
1500	.2981	.1903	.1498	.1232	.1035	.0881
1600	.2981	.1866	.1455	.1187	.0990	.0836

## SPE WATER CONTENT VS. CURRENT DENSITY

TABLE IV

TEMP DEG F	CURR DEN	H2 SIDE ACTIVITY	WATER CONTENT	RESISTANCE MOHM-SQ IN.	GIBBS VOLTAGE	IDEAL VOLTAGE	LOSS ASF
220	100	.9899	.2456	12.6356	1.2089	1.2001	15.36
	200	.9773	.2142	13.1398	1.2089	1.1907	14.68
	300	.9630	.1928	13.6008	1.2090	1.1806	14.14
	400	.9473	.1763	14.0397	1.2090	1.1700	13.69
	500	.9303	.1627	14.4697	1.2091	1.1588	13.29
	600	.9124	.1511	14.8995	1.2091	1.1471	12.94
	700	.8936	.1410	15.3355	1.2092	1.1346	12.62
	800	.8741	.1320	15.7827	1.2092	1.1216	12.32
	900	.8542	.1239	16.2454	1.2093	1.1078	12.05
	1000	.8337	.1166	16.7278	1.2094	1.0932	11.79
	1100	.8130	.1099	17.2339	1.2094	1.0778	11.54
	1200	.7922	.1038	17.7681	1.2095	1.0614	11.31
	1300	.7712	.0982	18.3356	1.2095	1.0440	11.09
	1400	.7502	.0930	18.9408	1.2096	1.0255	10.88
	1500	.7294	.0881	19.5911	1.2097	1.0056	10.68
	1600	.7087	.0836	20.2924	1.2097	.9842	10.49

CELL PERFORMANCE VS. CURRENT DENSITY

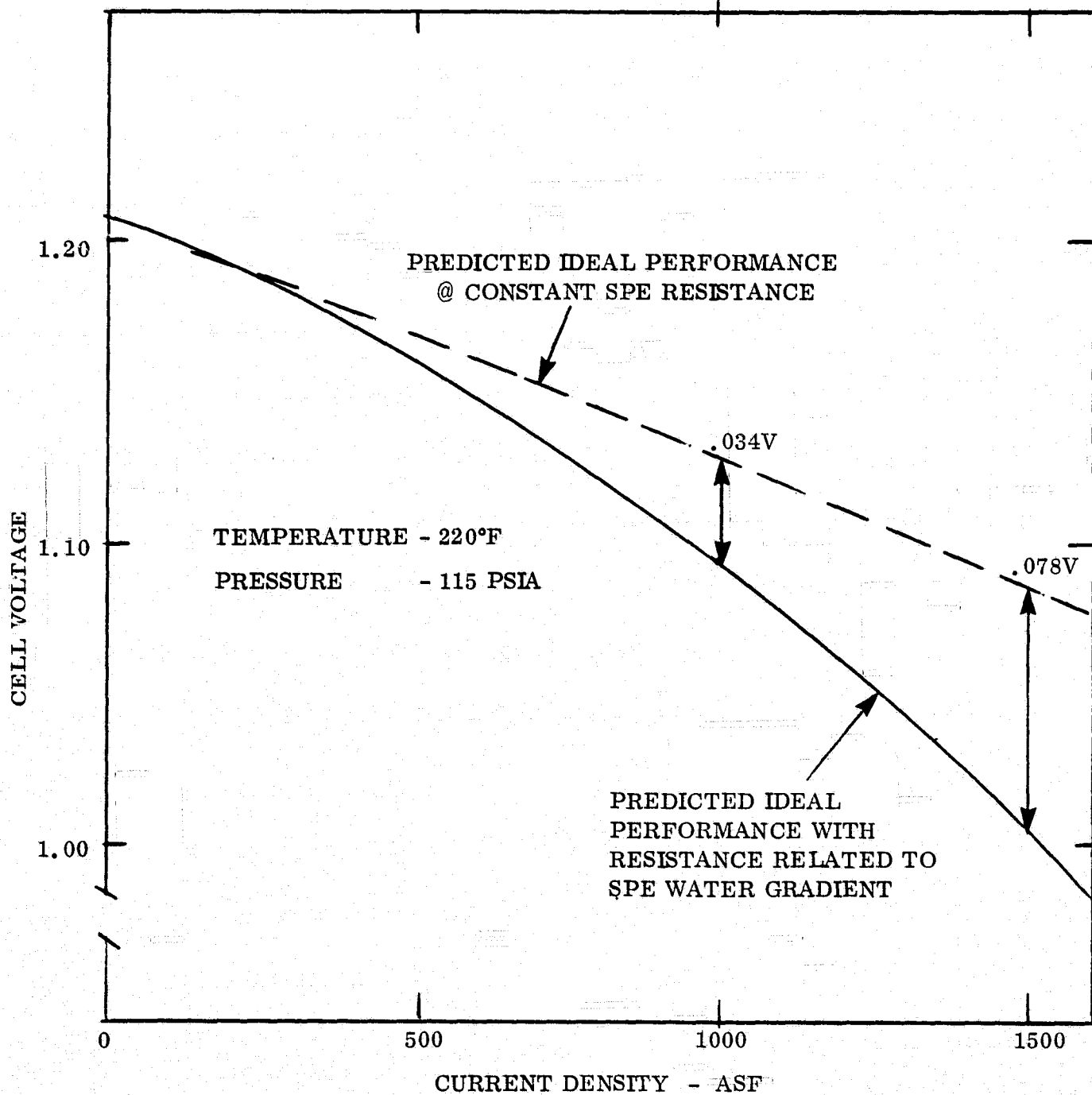


Figure 15.

COMPUTER MODEL

THEORETICAL PERFORMANCE

CONSIDERING TEMPERATURE, PRESSURE AND INTERNAL  
SPE RESISTANCE CELL



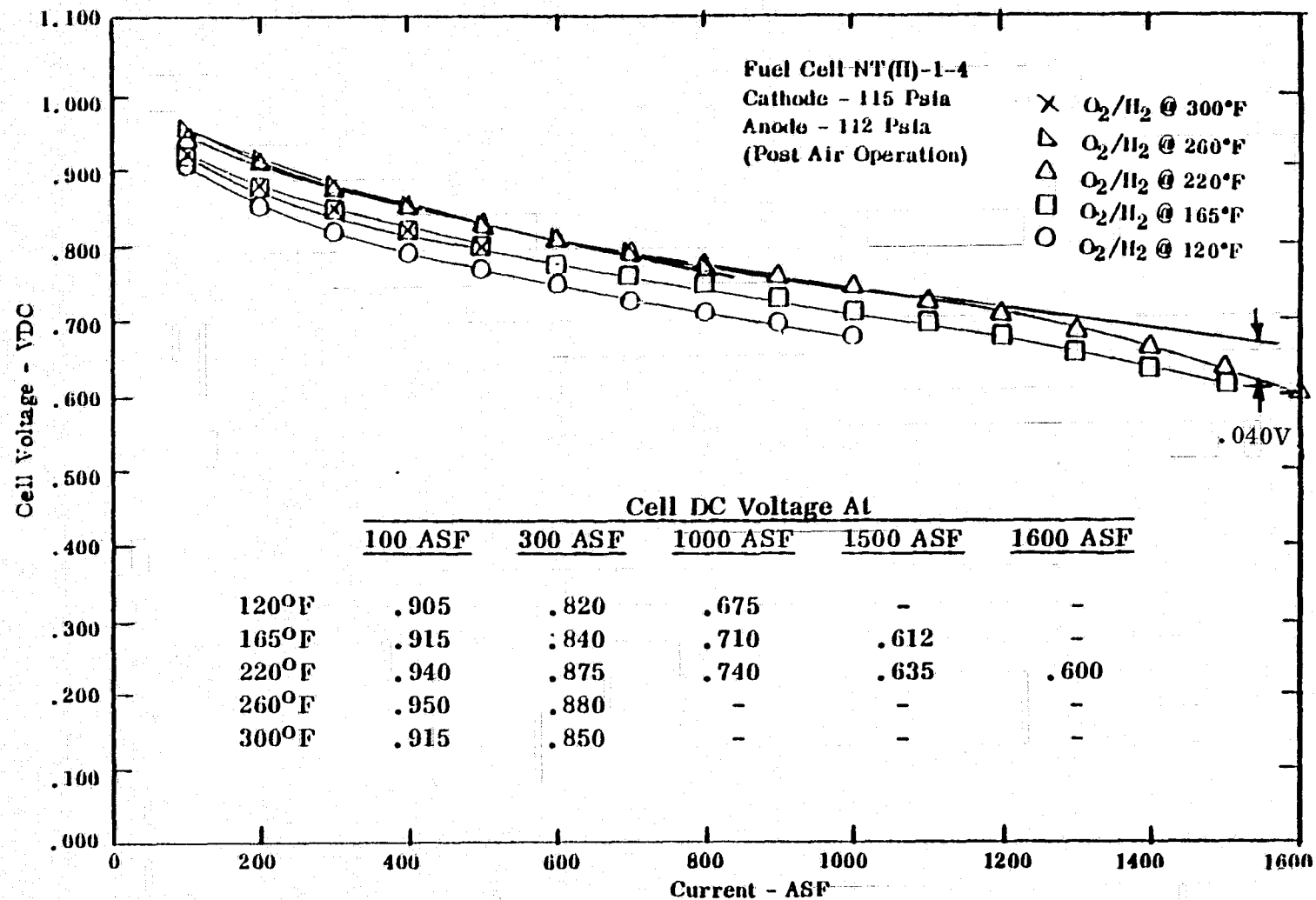


Figure 16.  $O_2/H_2$  - High Current Density Performance



Increased water content could result in increased "Proton Pumping" which would negate the advantage of increased water diffusion.

In the present hardware design, the introduction of liquid water into the anode active area results in anode flooding and rapid voltage fall off. A development program beyond the scope of this program would be required to perfect a non-flooding/non-masking anode configuration with  $H_2O$  injected into the active area. Initial development work in area is presently planned for a GE in-house program.

#### 3.1.1.2 High Operational Temperatures

The Phase II performance vs data revealed considerably lower performance levels at 300°F than at 220°F. This lower performance was noted even at the lower current densities near open circuit. As in the case of the high current density testing, water slugs were thought to have had some influence on the performance. The water slug frequently on the hydrogen side was even higher at the 300°F operating level.

As part of this sub-task element, two cells were fabricated and operated in the hydrogen trap hardware which minimized the hydrogen liquid water introduction. Table V and Figure 17 displays the performance levels. Even with the trap hardware the level of performance at 300°F and low current densities was approximately 0.050 volt lower than the 220°F performance at the same total pressure.

With these results, the computer was once again enlisted for a determination of theoretical performance. Figure 18 displays the theoretical ideal cell voltage vs operating temperatures and pressures. Figure 19 shows the ideal cell performances vs current density and operating temperature with a fixed total pressure of 115 psia. The Figure depicts a reduced low current density voltage at higher temperature and constant total pressure. The 50 millivolt reduction between the 220°F and 300°F ideal open circuit voltage (Gibbs free energy voltage) is the result of the variation of specific heat and the oxygen/hydrogen partial pressures. The 50 millivolts shown in the model agrees quite favorably with the difference observed in the real hardware thus leading to the conclusion that the lower performance at 300°F at low current densities is the result of a shift in the Gibbs free energy voltage.

#### 3.1.1.3 Catalyst Reductions

During Phase II a number of cells were evaluated with reduced noble metal loading on the anode catalyst. Without exception, these cells showed near normal IR free initial performance; however, with operating time both IR free and DC voltage was observed to deteriorate. This is in marked contrast to the base line loading of 4 mg/cm<sup>2</sup> which displays less than 1  $\mu$  volt (DCV) decay per cell hour.





TABLE V

TASK 1.1.2 HIGH OPERATIONAL TEMPERATURES

115 psia - Cathode

112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F .905 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F .820 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F .675 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F .940 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F .875 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .740 VDC	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F .635 VDC	O <sub>2</sub> /H <sub>2</sub> 1600 ASF 220°F .600 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F .915 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F .850 VDC
NT(III)-1.2-1	100% Pt Black Anode	-.042	-.056								
NT(III)-1.2-2	100% Pt Black Anode	-.022	-.035	-.093	-.020	-.038	-.073	-	-	-.044	-.080

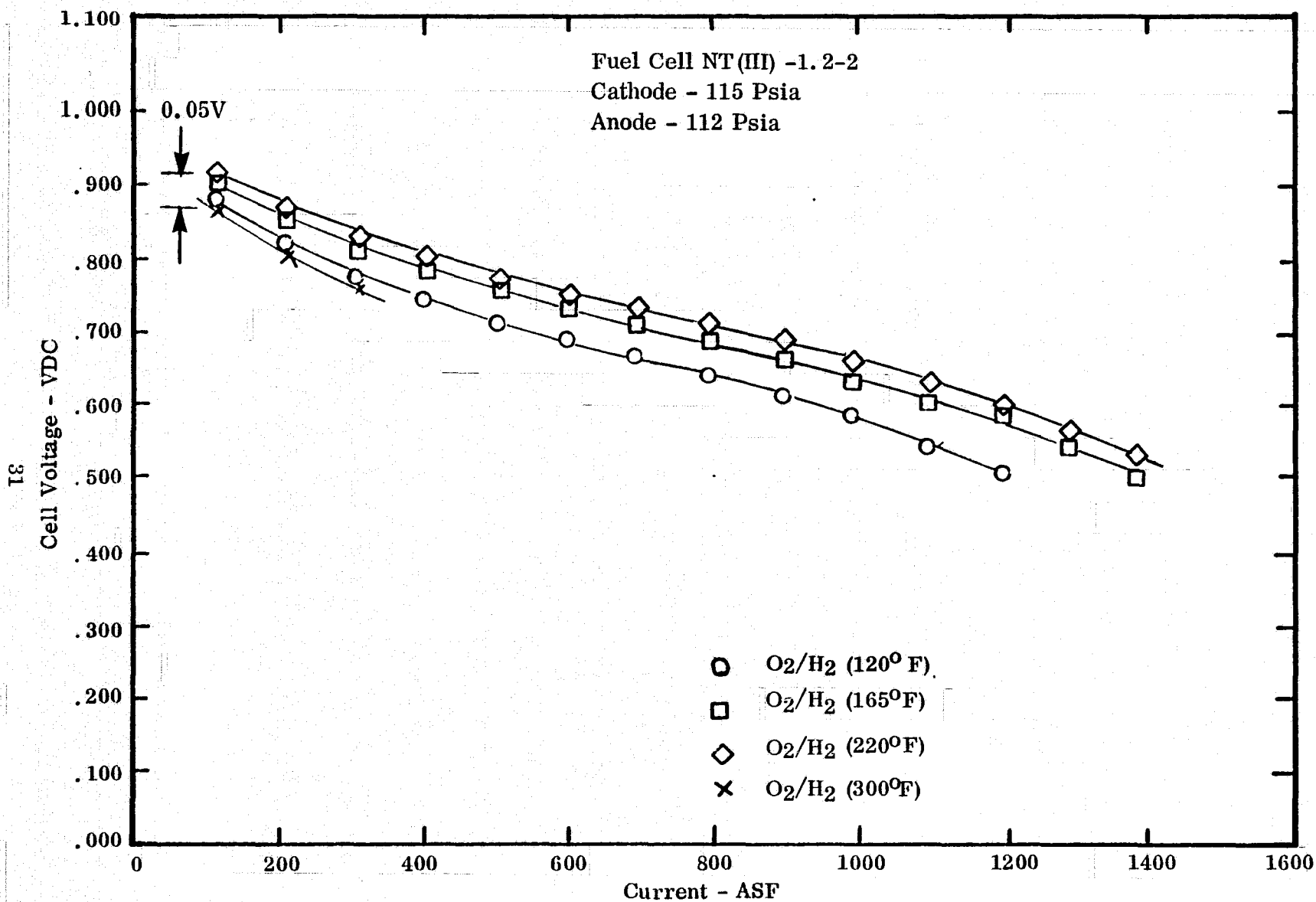
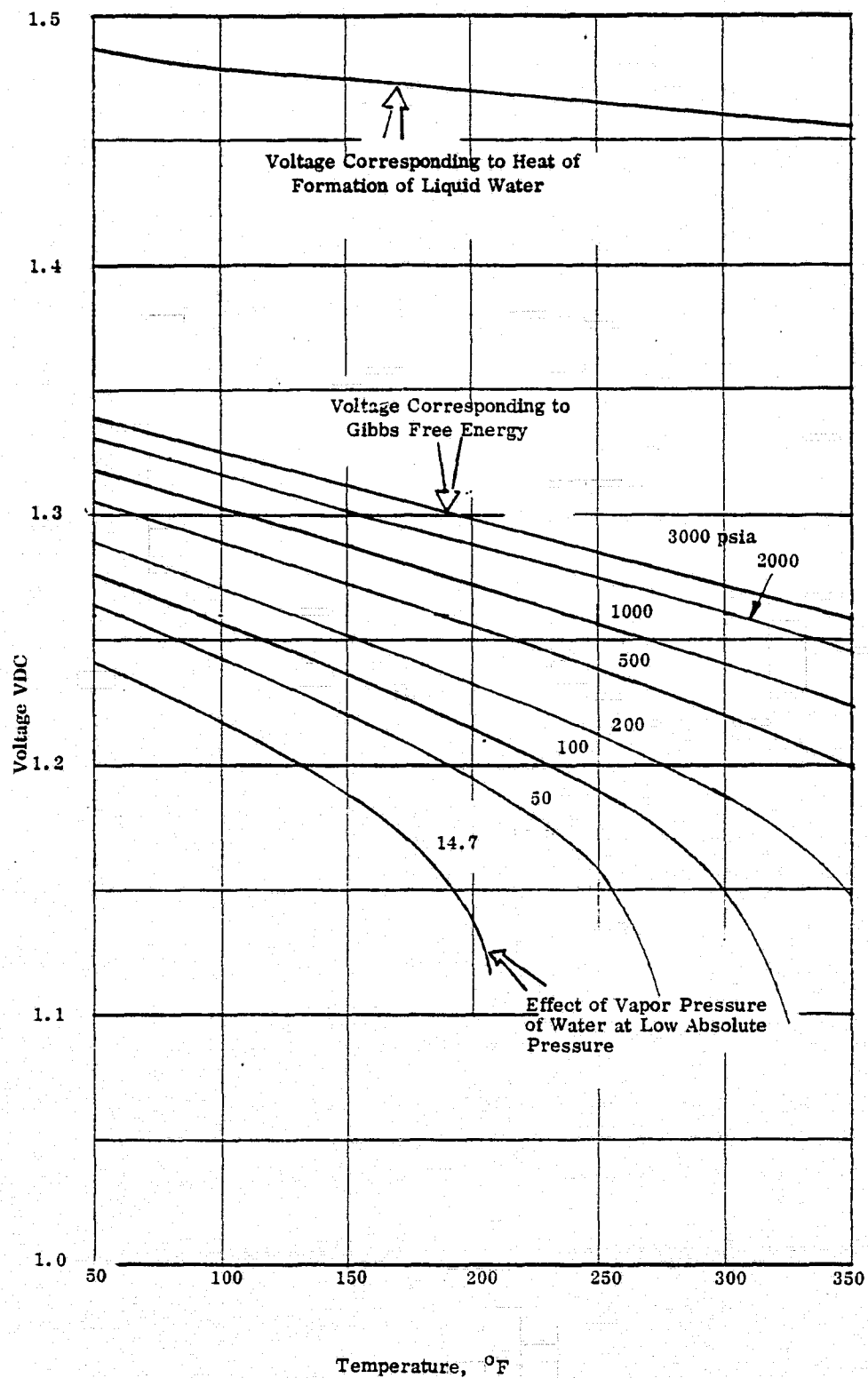
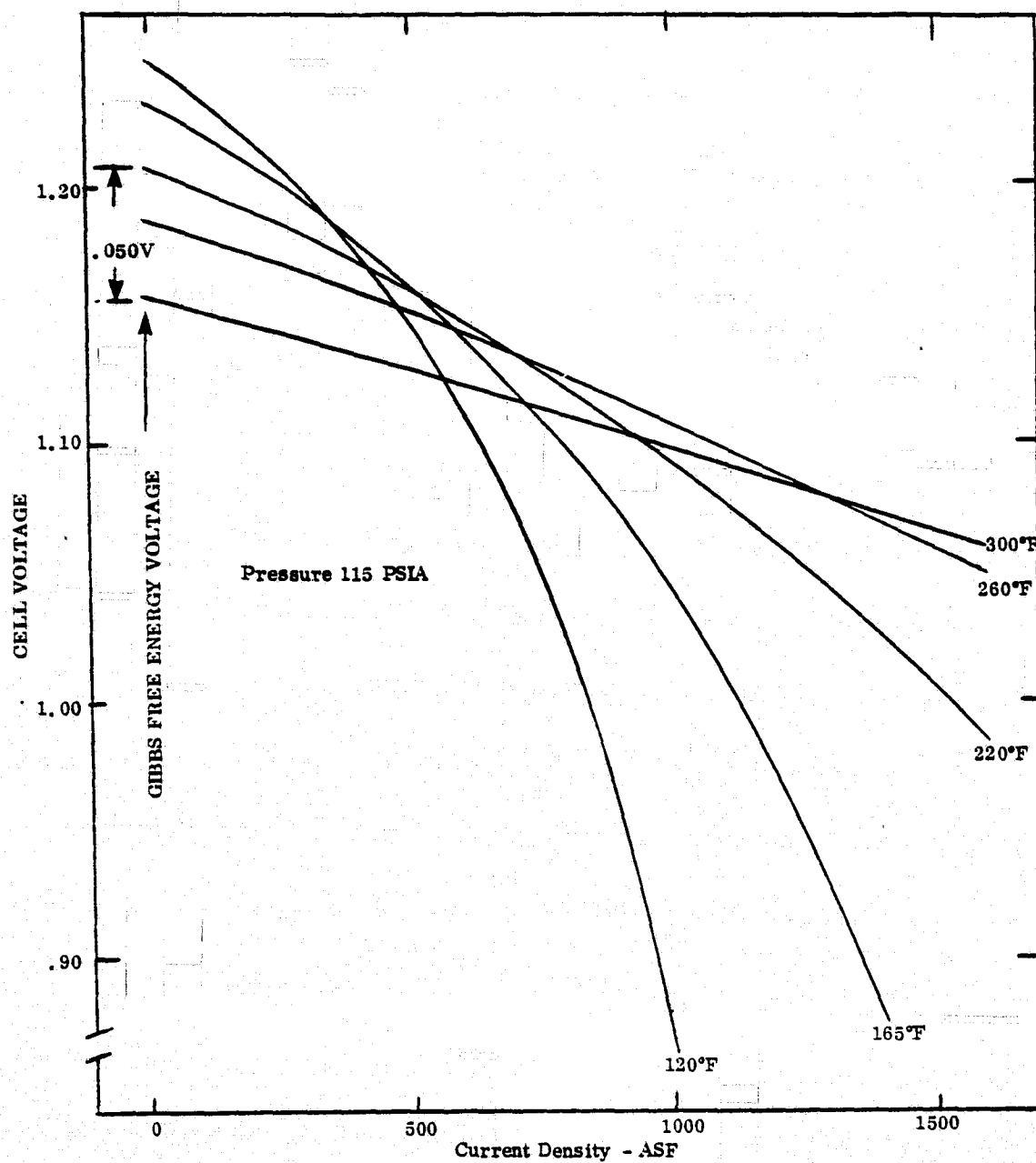


Figure 17. O<sub>2</sub>/H<sub>2</sub> Performance vs. Temperature





Theoretical Voltage Vs. Temperature  
Figure 18.



COMPUTER MODEL

PREDICTED IDEAL PERFORMANCE VS. CELL OPERATING TEMPERATURE

Figure 19.



Cell NT(II)-2-8 was one of the cells tested during Phase II and was on test at the start of Phase III. This cell had an anode of 0.05 mg/cm<sup>2</sup> platinum on 4 mg/cm<sup>2</sup> graphite. Cell NT (II)-7-8 exhibited the same high initial performance with degradation with time.

The performance degradation and performance fluctuation appeared very similar to the characteristics of a platinum anode cell being fueled with CO-contaminated fuel. It was postulated that a small amount of CO (PPM range) in the commercial grade hydrogen might be sufficient to contaminate the lightly loaded anode.

Hydrogen zero gas of very high purity was obtained and fed into Cell NT(II)-2-8. The performance of the cell which had degraded considerably in performance, showed no improvement, in fact, continued to degrade over the five days of operation on the hydrogen zero gas.

Cell NT (II)-2-8 was removed from test and underwent anode electrode surface area determination utilizing the CO absorption technique. The following test results were obtained:

- Total Active Area -160 m<sup>2</sup>/G
- Electrochemically Available Active Area - 88 m<sup>2</sup>/G

Although the test results showed a marked difference between the total and electrochemically active areas, both data points were considered questionable because of the high values of platinum surface area (i.e. 20 m<sup>2</sup>/G would be considered normal for a platinum black electrode). It was considered that the graphite portion of the electrode was in fact influencing the test results.

To separate the graphite/platinum test results, it was decided to fabricate two new cells. These cells were fabricated to the 1977 base line configuration except:

- Cell NT (III) 1.3-1 (4 mg/cm<sup>2</sup> graphite anode).
- Cell NT (III) 1.3-2 (0.05 mg/cm<sup>2</sup> platinum sputtered on 4 mg/cm<sup>2</sup> graphite anode).

These cells were subjected to the CO active area determination tests with the following results:



Surface Area Measurements		
	<u>Electrochemically Active Area</u>	<u>Total Active Area</u>
Cell NT (III)-1. 3-1		
Graphite	.34 M <sup>2</sup> /G	.40 M <sup>2</sup> /G
Platinum	-	-
Cell NT (III)-1. 3-2		
Graphite*	.34 M <sup>2</sup> /G	.40 M <sup>2</sup> /G
Platinum	17.24 M <sup>2</sup> /G	15.8 M <sup>2</sup> /G

\* Assumed the same as NT (III)-1. 3-1

The results obtained in these CO tests were considerably more realistic than previous results and show that the graphite electrode extender does in fact influence the surface area measurements.

Cell NT (III)-1. 3-2 was then set up in a test facility and activated. Initial performance shown on Table VI was in the range of the pre-air activated base line when adjusted for internal resistance, (i. e., Cell NT (III)-1. 3-2 had an internal resistance approximately 0.01 ohm higher than base line). Continued operation of the cell revealed a performance decay of 0.159 volt at 100 ASF and 120°F over a five day period. (See Figure 20). The operational temperature was increased to 165°F and although initial performance was greatly improved, continual performance decay was noted over an additional four days of operation.

Cell NT (III)-1. 3-2 was removed from test following 10 days of operation. A repeat of the electrochemically active area measurement, utilizing the CO absorption technique, was made. This measurement showed nearly a 50% reduction in the electrochemical active area of platinum (see Table VII.)

Additional effort into the determination of the cause of surface area reduction was not conducted as part of this program because the amount of noble metal utilized on the typical space fuel cell considering the newly established high current densities, would not have a significant cost impact.

#### 3.1.1.4 Electrolyte Modifications

Three cells were fabricated and evaluated as part of this sub-task element. Table VIII displays the initial performance of each of these cells.

Cell NT (III)-1. 4-1 was fabricated utilizing platinized radiation grafted membrane in place of the base line Nafion®. This particular membrane underwent a special series of chloride removal steps. The chloride was identified as a contaminating element during initial processing.



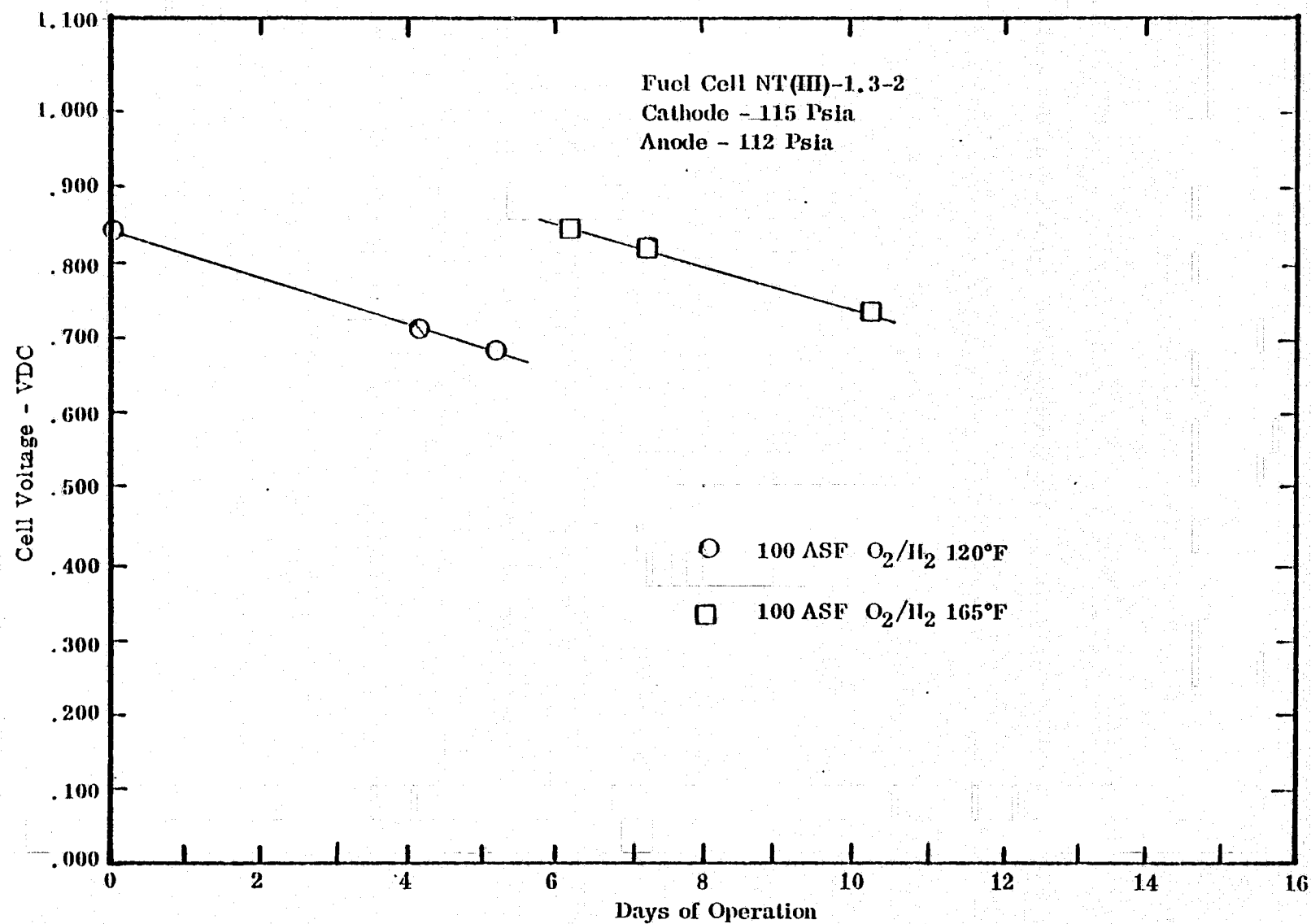


Figure 20.  $O_2/H_2$  Performance vs. Temperature



TABLE VI

TASK 1.1.3 CATALYST REDUCTIONS

115 psia - Cathode

112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F .905 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F .820 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F .675 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F .940 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F .875 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .740 VDC	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F .635 VDC	O <sub>2</sub> /H <sub>2</sub> 1600 ASF 220°F .600 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F .915 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F .850 VDC
NT(III)-1.3-1	4mg/cm <sup>2</sup> Graphite Anode										
NT(III)-1.3-2	0.05mg/cm <sup>2</sup> Pt sputtered on 4 mg/cm <sup>2</sup> graphite anode.	-.063	-.144								



TABLE VII

	<u>Electrochemically Active Area</u>	<u>Total Active Area</u>
Cell NT (III)-1.3-1		
Graphite	.34 M <sup>2</sup> /G	.40 M <sup>2</sup> /G
Platinum	-	-
Cell NT (III)-1.3-2 (pre Operation)		
Graphite	.34 M <sup>2</sup> /G	.40 M <sup>2</sup> /G
Platinum	17.24 M <sup>2</sup> /G	15.8 M <sup>2</sup> /G
Cell NT (III)-p. 3-2 (post operation)		
Graphite	.34 M <sup>2</sup> /G	
Platinum	9.95 M <sup>2</sup> /G	

\* Assumed the same as NT (III) -1.3-1



## TASK 1.1.4 ELECTROLYTE MODIFICATIONS

115 psia - Cathode

112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F .805 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F .820 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F .875 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F .910 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F .875 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .740 VDC	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F .635 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .600 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F .915 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F .860 VDC
NT (III)-1.4-1	RAI Membrane 100% Pt Black Anode	-.098	-.217								
NT (III)-1.4-2	Unplatinized Modified Nafion <sup>R</sup> 100% Pt Black Anode 10 Mils Thick	-.070	-.122		-.029	-.063					
NT (III)-1.4-3	Modified Nafion <sup>R</sup> Membrane 100% Pt Black Anode 10 Mils Thick	-.072	-.110		-.038	-.071					

Chloride contamination does not harm the membrane performance, but does effect the electrodes (i. e., chlorides forming HCl dissolving the platinum and also chlorides taking active sites). The source of chlorides appeared to be from the normal membrane preparation when chlorosulfonic acid is utilized in the sulfonation step.

In addition to the chloride clean up, cell NT (III)-1. 4-2 was assembled with less free water available during the hot press. This modification produced a superior anode attachment condition.

Fuel Cell NT (III)-1. 4-1 was initially operated at 120°F and 165°F. Figure 21 showed that the initial 120°F performance was considerably below the air activated 1977 base line performance. With internal cell resistance not significantly higher than base line, the lower performance was almost entirely caused by lower IR free performance. During this initial operation the HF in the product water was measured to be in the 20-30 PPM range compared to a base line cell of <1 PPM.

When the temperature was increased to 165°F and significant IR free performance increases were observed. Reductions in HF release to the 10 to 20 PPM range was also measured. (Figure 22 shows the improved DCV performance). Fuel Cell NT (III)-1. 4-1 was maintained at 165°F during which time performance improved until the tenth day. From the tenth day to the 20th day performance remained stable. (See Figure 21). Also during this time HF levels dropped to the 5 PPM range. On the twenty-first day of testing, the cell temperature was increased from 165°F to 220°F. The HF release rate increased from the 5 PPM range to the 15 PPM range following this temperature increase. As testing continued, the HF release dropped to the 10 PPM range. Over the 20 days of operation at 220°F, a slow performance decay associated with increased internal resistance was observed. Two test anomalies (slight pressure reversal on the thirty second day and a power failure on the thirty eighth day) appeared to aggravate the resistance somewhat.

Cell failure occurred on the fortieth day of endurance testing with a cross membrane leakage. A tear down of the cell showed no evidence of polymer chemical degradation, (i. e., no membrane blistering). This cell, although it ran for only about 1000 hours, did demonstrate significant improvement in performance and life over the previous RAI membrane cell tests.

Process improvements in the radiation grafted membrane were investigated under the GE/DECP water electrolysis programs. Processing of a new cell with these improvements was started during Phase III and will be completed during Phase IV.



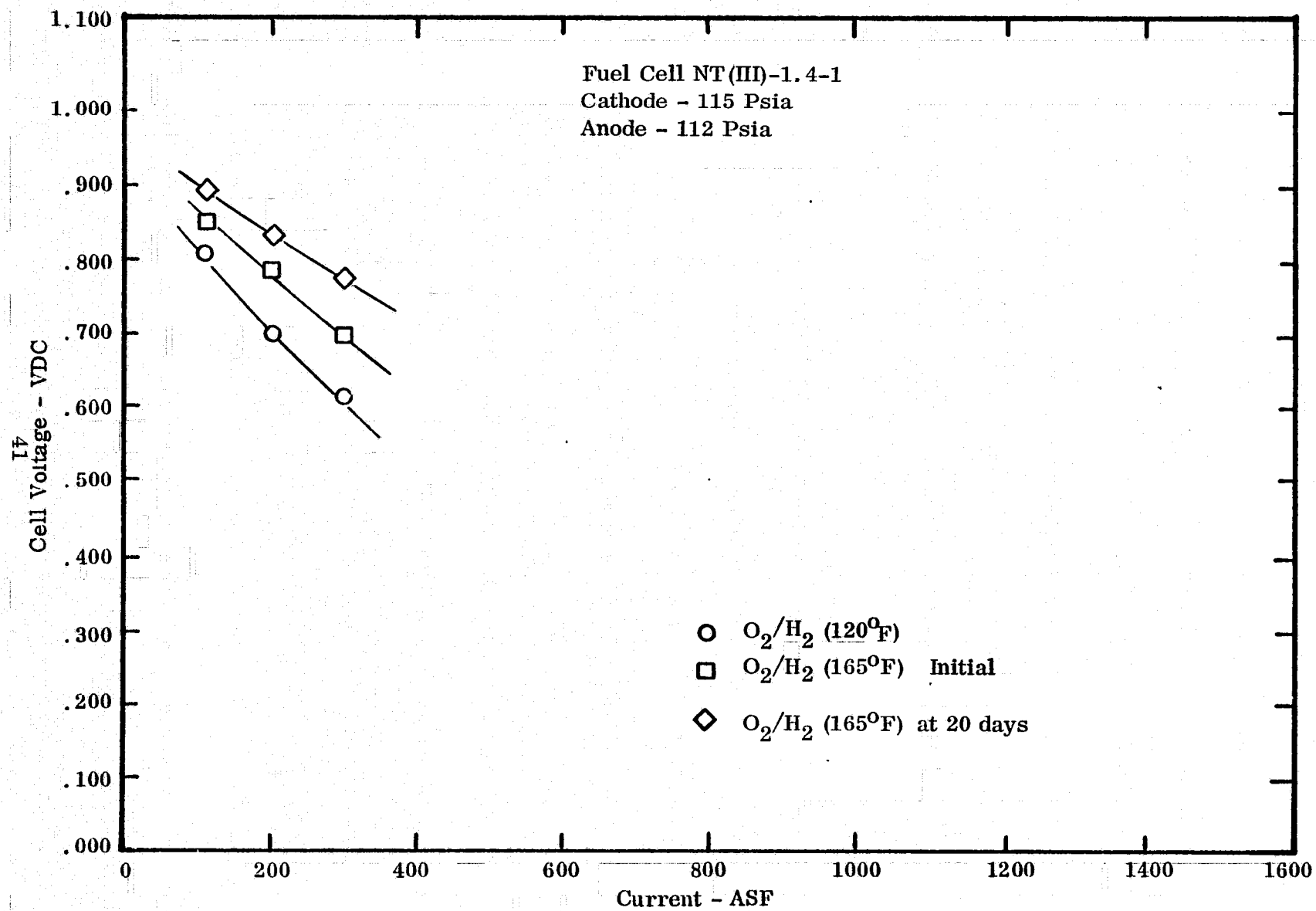


Figure 21.

 $O_2/H_2$  Performance vs. Temperature

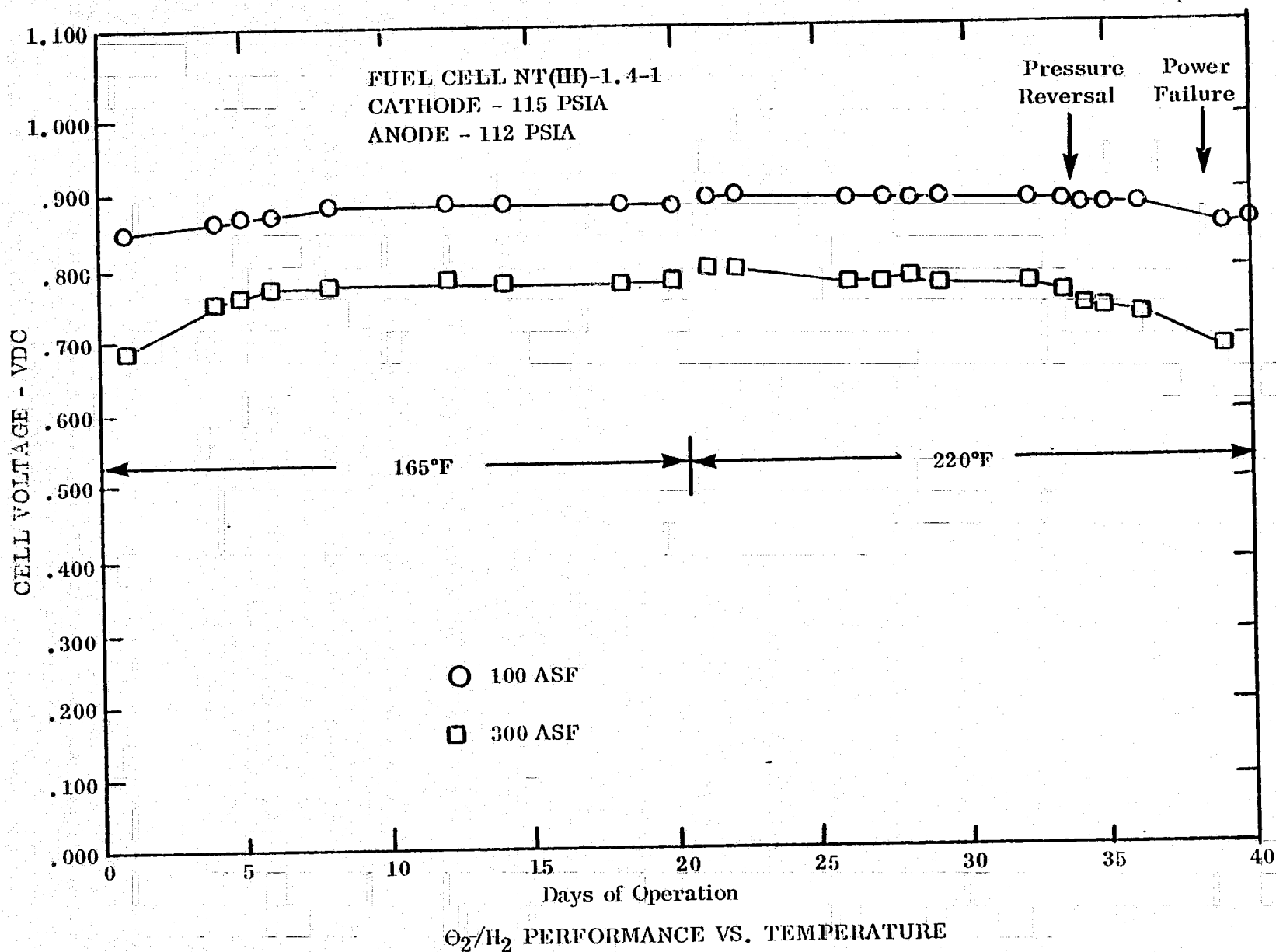


Figure 22



Two cells were evaluated with a modified Nafion® membrane. The modified membrane was the product of a proprietary process of a third party. Claims that improved resistance and diffusion could be obtained without loss in electrochemical stability were indicated.

An unplatinized Nafion® membrane, modified by the proprietary process was used in the fabrication of an electrolyte cell (NT (III)-1.4-2). The unactivated 1000 Hz resistance of this cell was essentially the same as that encountered in normal Nafion® electrolyte cells.

Table VIII and Figure 23 display Cell NT (III)-1.4-2 performance. Although the initial performance at 120°F was not considered unusual for the 10 mil thick electrolyte, at temperatures of 220°F, performance appeared slightly higher than expected. Internal resistance was also lower than expected by some 20-30%. The only adverse observation made during the 200 hours of testing concerned a very high HF release into the product water, suggesting a rapid chemical degradation of the polymer. The HF release rate was in the 100-200 PPM range at an operational temperature of 220°F.

Cell NT (III)-1.4-3 was fabricated with platinized modified Nafion® membrane. Prior to actual activation, extensive diffusion testing was performed. The results indicated that this modified Nafion® membrane had approximately 50% of "normal" Nafion® diffusion.

Cell NT (III)-1.4-3 was activated and operated at approximately the same performance level as Cell NT (III) 1.4-2. (See Table VIII and Figure 24.) The cell was operated for approximately 200 hours at 220°F, during which time the HF release rate stabilized in the 2-3 PPM range as compared to the 100-200 PPM range for Cell NT (III) 1.4-2 with its unplatinized membrane.

#### 3.1.1.5 Performance Evaluation

The purpose of this sub-task element was to gain insight into the observed performance improvement of Cell NT (II)-1-4 following H<sub>2</sub>/air operation when returning to H<sub>2</sub>/O<sub>2</sub> operation.

Cell NT (III)-1.5-1 (base line) was activated with initial performance displayed in Table IX. This cell was operated on H<sub>2</sub>/air for four hours at current densities up to 800 ASF. Figure 25 displays the pre and post-air operation on H<sub>2</sub>/O<sub>2</sub>. Although there was not a 50 millivolt improvement in DCV an IR free voltage improvement of 50 millivolts at 1000 ASF was observed. The increase in cell resistance during air operation is believed to have been caused by a temporary sub-saturation of the high flow reaction air.



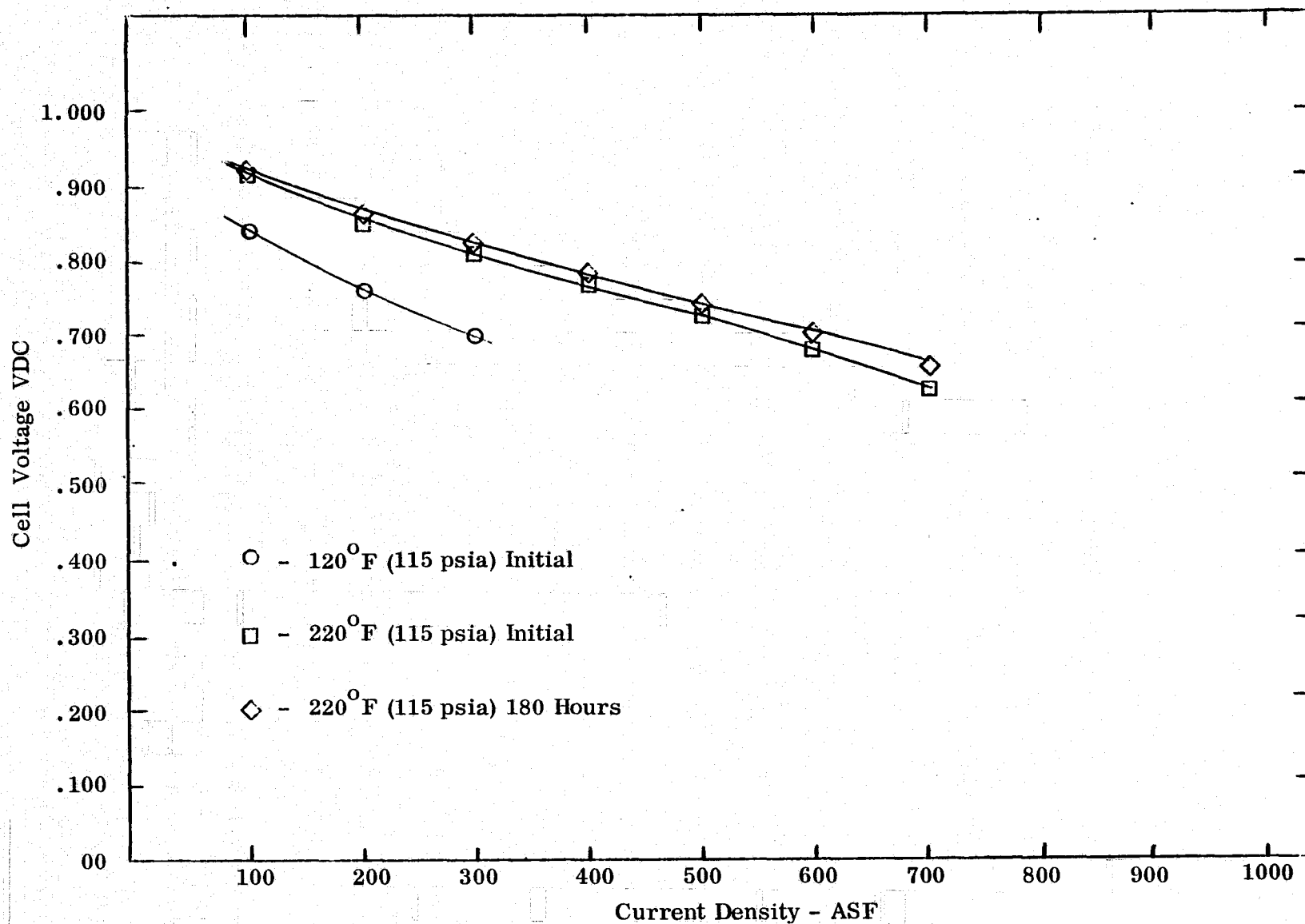


Figure 23. Cell NT(III) 1.4-2 (Unplatinized Modified Membrane)



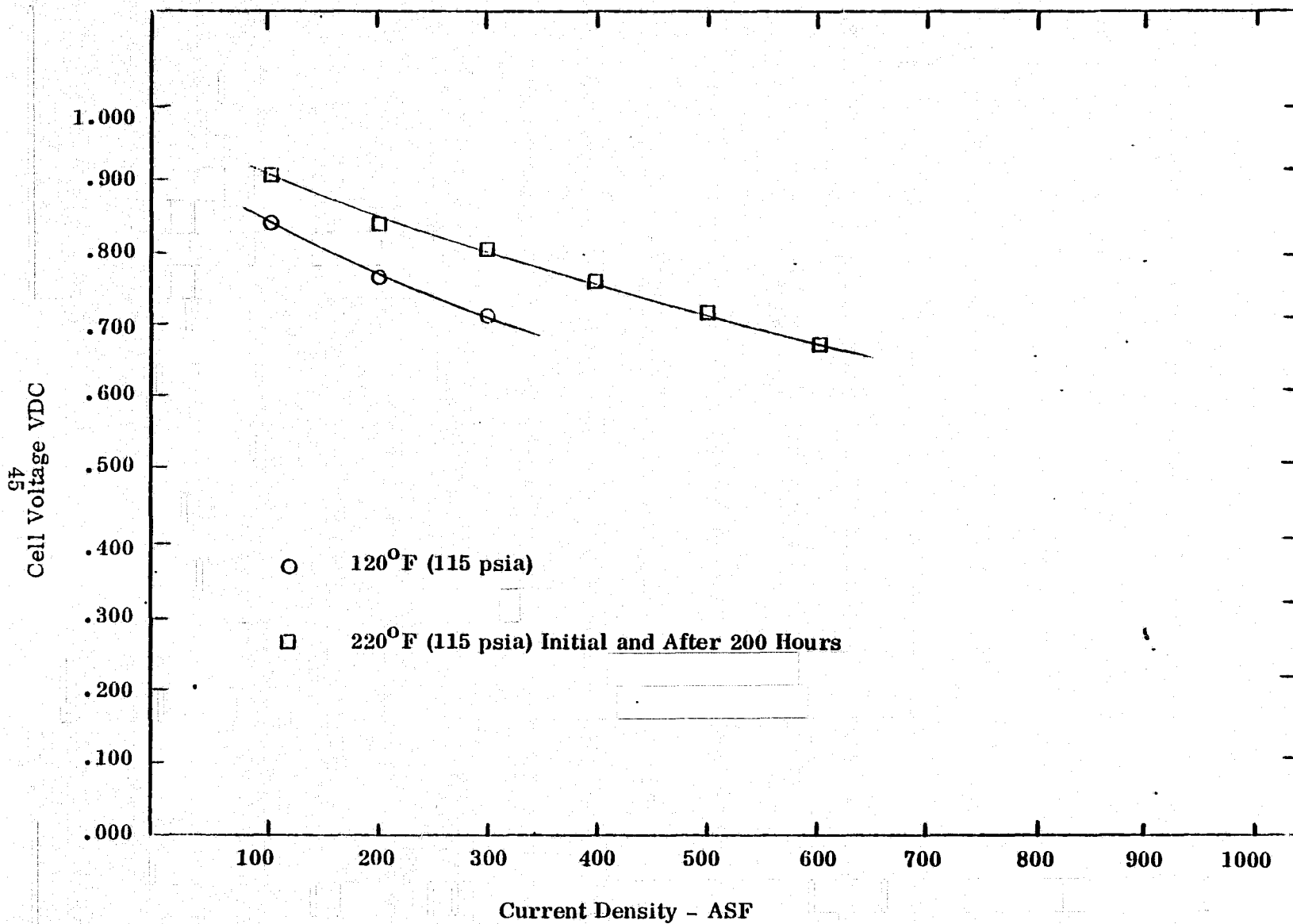


Figure 24. Cell NT (III) 1.4-3 (Platinized Modified Membrane)





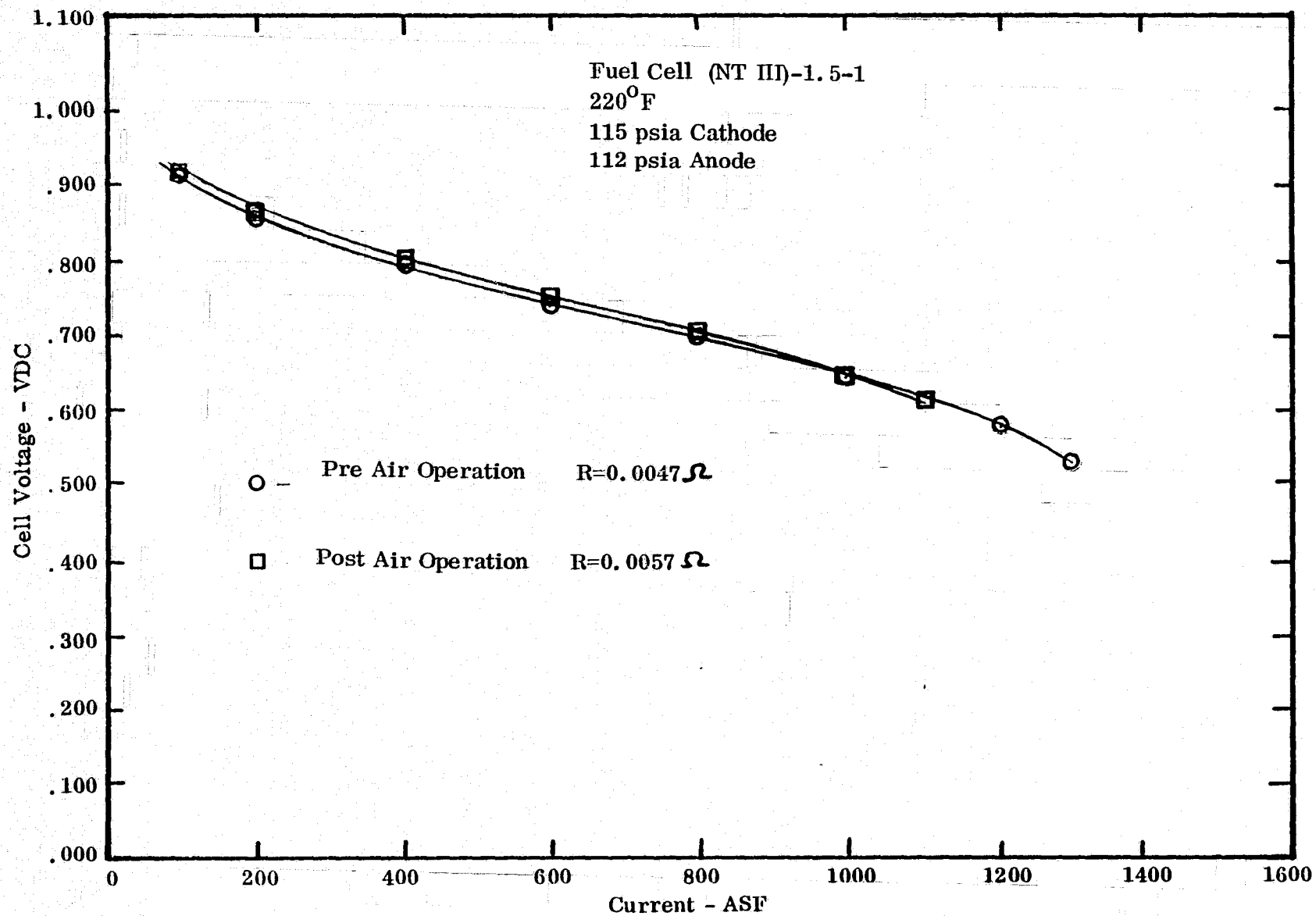
TABLE IX

## Task 1.1.5 Performance Evaluation

116 psia - Cathode

112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F .905 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F .820 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F .675 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F .910 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F .875 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .740 VDC	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F .635 VDC	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F .600 VDC	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F .915 VDC	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F .850 VDC
NT(III)-1.5-1	100% Pt Black Anode	-.039	-.049		-.031	-.046	-.091				
NT(III)-1.5-2	100% Pt Black Anode										
NT(III)-1.5-3	100% Pt Black Anode										
	Cold Cathode Press										
NT(III)-1.5-4	100% Pt Black Anode	-.023	-.040		-.019	-.049					
	Cold Cathode Press										
W3 (IR and D	Conductive Wet-	-.064	-.087		-.015	-.036					
	proofing										
	100% Pt Black Anode										

Figure 25.  $O_2/H_2$  Performance vs. Temperature

The product water of Cell NT (III)-1.5-1 which was collected before, during and after hydrogen/air operation was analyzed for potential contaminants. Although small amounts of chlorides and sodium were identified, the rate of release was approximately constant throughout the test period. A preliminary conclusion reached, due to the fact that Cell NT (II)-1.5-1 showed a 50 millivolt IR free increase at 1000 ASF following air operation, was that the common variety of contaminating species were not being cleansed from the cell during air operation and thus was not the mechanism for improved performance.

An analysis of the log of Cell NT (II)-1-4 showed that an automatic shutdown, probably caused by excess  $H_2$  side water, had occurred just prior to the operation on air. The shutdown/restart operation was then considered to be related to the optimization of cell performance. In this regard a new Cell, NT (III)-1.5-2 (base line) was assembled and a series of activations performed where the amp hours of the electrolysis starting procedures were varied. Table X shows the results of this type of activation. A base line cell is activated for 22.5 amp minutes at a maximum of 2.0 amps.

The series of electrolysis activations suggested that excess water trapped in the wetproofing film might be the cause of lower cell performance. The hypothesis for this mechanism is as follows:

- A variable amount of moisture is trapped in the wetproofing film during cell fabrication when high pressure steam is directly available for intrusion into the pore structure.
- A portion of this moisture is driven out of the wetproofing during electrolysis start-up when proton pumping and water consumption tend to dry the oxygen catalyst/wetproofing/electrolyte interface.
- Existing excess moisture is also removed when operating the cell at high current density, utilizing air as the source of oxidant. The lower cell efficiency with air produces larger cathode drying thermal gradients.
- Once this excess moisture is removed, it does not return, as no operational or storage mechanism (i. e., no high pressure steam) is provided.

To generate evidence in support of this hypothesis a fabrication technique, involving attachment of the cathode wetproofing at room temperature was developed.



TABLE X  
Cell Activation Data

<u>Activation Number</u>	<u>Amp-Minutes Electrolysis</u>	<u>Current Amps</u>	<u>Room Temperature - 10 psig 100 ASF Voltage</u>
1	2.5	.5	.489
2	2.5	.5	.600
3	5.0	1.0	.556
4	5.0	1.0	.568
5	10.0	1.0	.564
6	20.0	2.0	.626
7	20.0	2.0	.682
8	20.0	2.0	.700
9	40.0	4.0	.743



The fabricated cell (NT (III)-1.5-3 with a cold cathode press) was installed utilizing the vacuum start approach. Initial performance at room temperature and 25 psia pressure was 50 mv higher than the normal base line cell, which is hot pressed and electrolysis-activated. However, continued operation on super-saturated reactants resulted in lower standard performance by the time an operational temperature of 120°F was reached.

In view of the above results, it was postulated that liquid water is trapped within the cathode wetproofing during hot fabrication and that the use of super-saturated reactants to assure non-drying gradients may also contribute to a moisture buildup within the cathode wetproofing, through a direct condensation from the reactant stream. An attempt to verify this postulation was made by fabricating a cold cathode press cell and operating it with unhumidified reactants.

The initial testing of Cell NT (III)-1.5-4 showed no significant improvement in electrical performance. (See Table IX). The cell was operated for 2 days with no change in performance.

At this point, the performance gain postulated mechanism with air activation appeared inconclusive. However, other ongoing activities suggested that a new base line configuration with a non-conductive wetproofing be evaluated. Air activation of that new configuration could then be evaluated.

The reassessment that resulted in the judgement that future performance and endurance analyses should be performed on cells containing conductive wetproofing was based on the following factors:

- The configuration demonstrated over 2000 hours of completely stable performance on scaled-up Unit NT-03. This has dispelled many of the concerns over oxidation of the conductive wetproofing graphite structure at operating voltages.
- A conductive wetproofing is desirable for scaled-up hardware to minimize IR losses.
- Because the conductive wetproofing configuration fully supports the electrolyte polymer on both sides, facility failures of the type involving oxygen loss would not damage the cells.
- Extrapolated performance from Cell NT-03, and from the 10 mil thick cells on the IR and D Program with conductive wetproofing, show an equivalent performance between the non-air activated baselines and the non-air activated conductive wetproofing configuration.



- Because the conductive wetproofing configuration eliminates the cathode current collection screen and its 2-3 mil penetration into the polymer, greater structural strength of the polymer results by increasing the minimum cross section from approximately 2 mils to 4 mils.

IR and D Cell W-3 (5 mil Nafion<sup>®</sup> electrolyte with conductive wetproofing) was operated at base line conditions in order to obtain a performance comparison with the 1977 base line configuration, and other cells produced in the recent past. Table IX and Figure 26 display this performance. As can be seen, the performance of Cell W-3 was well within the range experienced from standard wetproofing cells with the open cathode gap and edge current collection.

During the Phase IV effort, additional activities are planned to assess the air activated performance of the conductive wetproofing cell configuration. At that time, a better understanding of the mechanisms involved will be the target of the investigations.

### 3.1.2 Endurance Evaluations

A total of 14 cells (See Table XI) were fabricated and evaluated as part of this sub-task. All 14 cells were of the non-conductive wetproofing type with an "open" gap cathode. All of these cells suffered premature failures from one or more of the following reasons:

- Loss of all plant oxygen supplies including back-up system by a facility solenoid overboard leakage development. This resulted in pressure reversal of several cells.
- Cathode screen puncture of the electrolyte in the perimeter compression area.
- Wrinkled membrane caused by improper gasket seal.
- H<sub>2</sub> regulator overboard leakage resulting in loss of all H<sub>2</sub> reactant.
- Low dew points in delivered reactants resulting from new "short" heaters.

It should be noted that, with the exception of the low dew point anomaly, the newly established conductive wetproofing configuration would have been considerably less prone to damage by the above test/facility difficulties. Endurance testing of this conductive wetproofing configuration will be initiated in Phase IV.



Cell Voltage - VDC

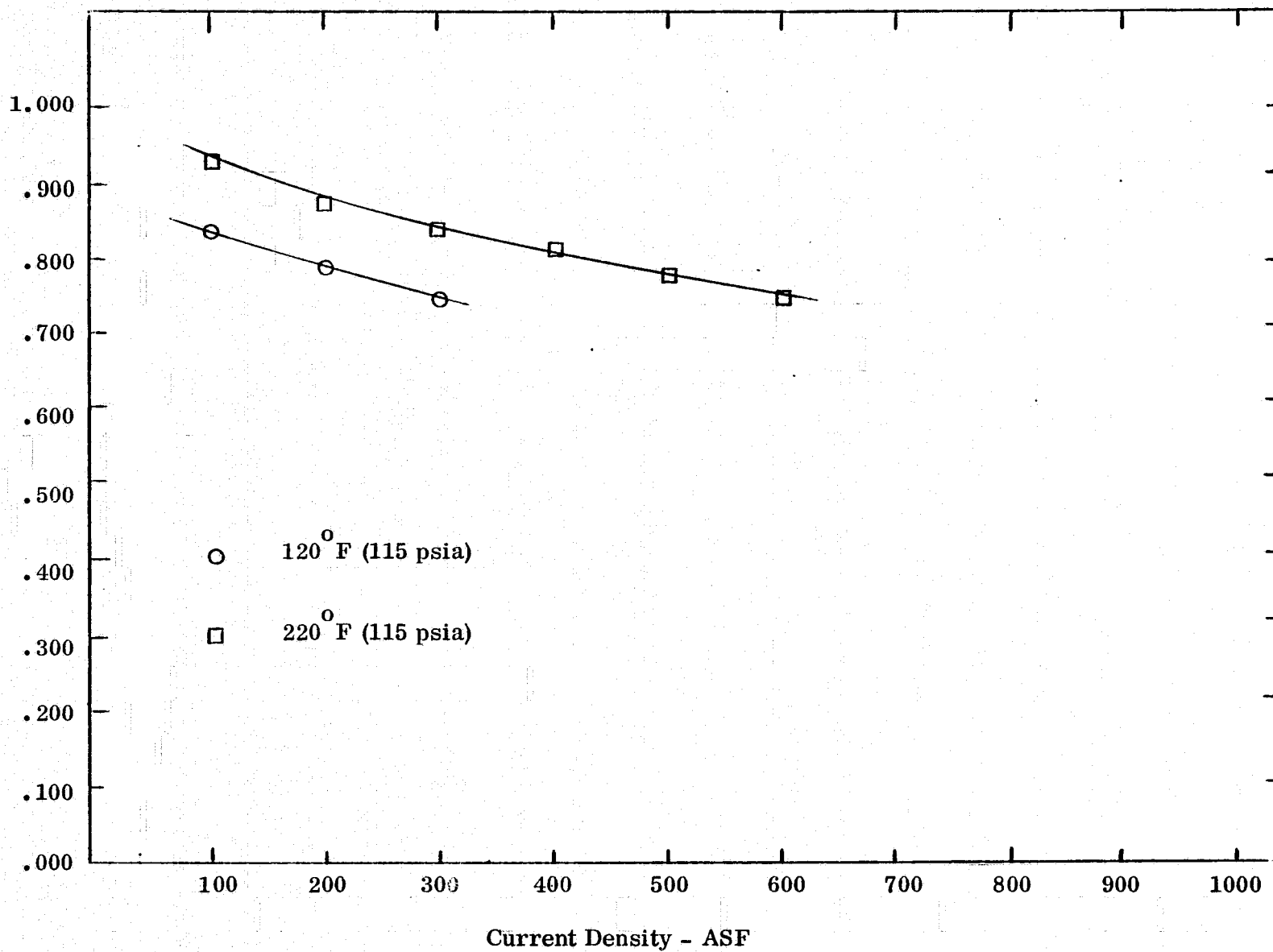


Figure 26. Cell W-3 (Conductive Wetproofing)



# Task 1.2 Endurance Evaluations

115 psia - Cathode

112 psia - Anode

Fuel Cell Number NASA (Phase III) Technology-Subtask-Cell NT (III) - X - X	Deviation from 1977 Baseline Fuel Cell	Performance Variance from 1977 Baseline Fuel Cell									
		O <sub>2</sub> /H <sub>2</sub> 100 ASF 120°F	O <sub>2</sub> /H <sub>2</sub> 300 ASF 120°F	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 120°F	O <sub>2</sub> /H <sub>2</sub> 100 ASF 220°F	O <sub>2</sub> /H <sub>2</sub> 300 ASF 220°F	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F	O <sub>2</sub> /H <sub>2</sub> 1500 ASF 220°F	O <sub>2</sub> /H <sub>2</sub> 1000 ASF 220°F	O <sub>2</sub> /H <sub>2</sub> 100 ASF 300°F	O <sub>2</sub> /H <sub>2</sub> 300 ASF 300°F
		.805 VDC	.820 VDC	.875 VDC	.910 VDC	.875 VDC	.740 VDC	.835 VDC	.600 VDC	.915 VDC	.850 VDC
NT(III)-2-1	100% Pt Black Anode	-.029	-.045		-.021	-.044					
NT(III)-2-2	100% Pt Black Anode	-.051	-.068		-.016	-.033					
NT(III)-2-3	100% Pt Black Anode	-.075	-.081		-.054	-.067					
NT(III)-2-4	100% Pt Black Anode	-.035	-.067		-.022	-.051					
NT(III)-2-5	100% Pt Black Anode	-.022	-.019		-.032	-.036					
NT(III)-2-6	100% Pt Black Anode	-.048	-.060		-.050	-.051					
NT(III)-2-7	100% Pt Black Anode	-.035	-.035		-.019	-.021					
NT(III)-2-8	100% Pt Black Anode	-.043	-.062		-.027	-.041					
NT(III)-2-9	100% Pt Black Anode	-.041	-.050		-.036	-.051					
NT(III)-2-10	100% Pt Black Anode	-.045	-.046								
NT(III)-2-11	100% Pt Black Anode	-.067	-.074		-.054	-.083					
NT(III)-2-12	100% Pt Black Anode	-.047	-.079		-.044	-.071					
NT(III)-2-13	100% Pt Black Anode	-.033	-.040		-.043	-.075					
NT(III)-2-14	100% Pt Black Anode	-.012	-.011		-.022	-.027					



### 3.2 Test Evaluation (0.7 Ft<sup>2</sup> Cell)

NT-02 (0.7 Ft<sup>2</sup>) was activated on August 23, 1976 and had accumulated 1672 hours of operation at the end of Phase II.

NT-02 continued testing into Phase III on H<sub>2</sub>/O<sub>2</sub> at 16 psia and 165°F and had accumulated 3076 hours of operation when a local power outage triggered an automatic shutdown of the system. Upon restarting the unit, the coolant system showed abnormally low flow and a high inlet to outlet differential pressure. Because proper cooling of the system was in question NT-02 was removed from test for disassembly and inspection. It was found that the polypropylene screen support material in the coolant cartridges had degraded and crumbled blocking coolant paths. Apparently the oxygen saturated coolant water chemically attacked the screen. The coolant water (distilled) uses oxygen as the pressurizing medium. Figure 27 displays performance of NT-02 on O<sub>2</sub>/H<sub>2</sub> at 120°F and 165°F as well as H<sub>2</sub>/air at 165°F.

In parallel with the NT-02 effort GE/DECP IR and D was conducting investigations of electrically conductive cathode wetproofing.

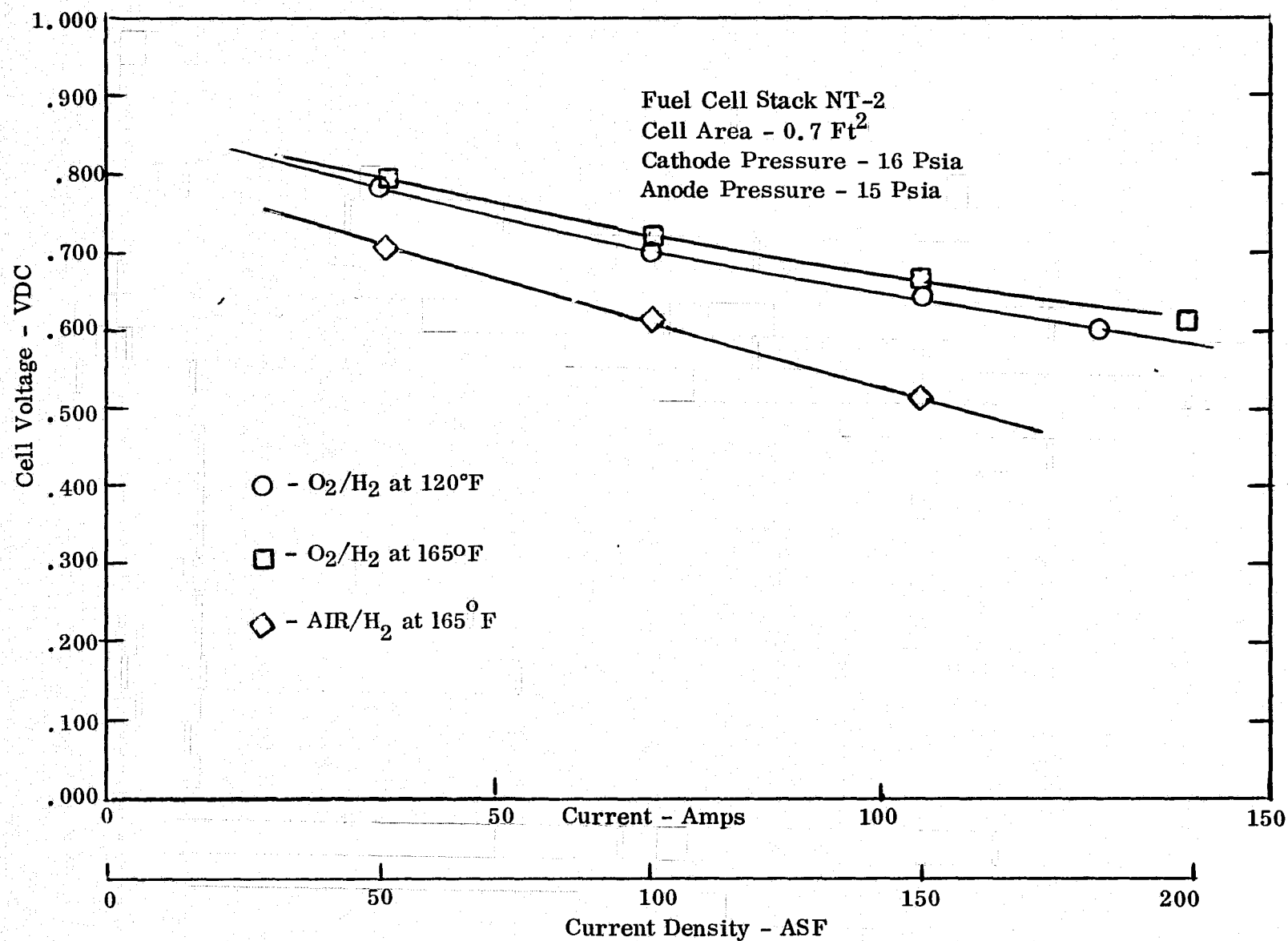
It was found that the primary advantages of a conductive wetproofing fuel cell configuration are as follows:

- The axial current flow characteristic eliminates edge current collection greatly simplifying a multiple cell stack, thus improving overall reliability.
- Because no screen is pressed into the SPE during manufacture, the risk of membrane puncture is greatly minimized. Also, thinner membrane (5 mil) can be used reducing IR loss.
- With the conductive wetproofing configuration the M and E is fully supported structurally on both sides eliminating pressure reversal sensitivity, thus improving durability.
- Performance is significantly better with the conductive wetproofing, especially when applied to multiple cell stacks.

When a successful conductive wetproofing cell was achieved, plans were made to retrofit the NT-02 unit with a cell of this configuration.

Because the timing of the NT-02 shutdown and disassembly somewhat coincided with the planned retrofit of the unit with a conductive wetproofing cell, redesign for NT-03 began.





Large Scale Cell Performance

Figure 27



The new configuration incorporated:

- Corrugated titanium coolant system trusses to replace the polypropylene screens.
- Conductive wetproofing to replace the interrupted Teflon wetproofing.
- Frame porting to replace port trusses for improved stack up.

Figure 28 shows a cross section of the new stack. On October 4, 1977, NT-03 began on load operation. At 2040 hours of operation, the system experienced an O<sub>2</sub> facility failure resulting in a complete pressure reversal. This incident had no effect on NT-03 giving further testimony to the superiority of the conductive wetproofing configuration.

A performance comparison is made between NT-02 and NT-03 in Figure 29. Also, the essentially invariant performance of NT-03 is displayed in Figure 30. Curves were made at initial activation at 1000 hours, 2209 hours and 2946 hours.

The extrapolated performance at 220°F and 115 psia is also shown on Figure 30. At the end of Phase III, NT-03 had accumulated 3388 hours of extremely stable performance at 16 psia and 165°F.

Throughout the NT-03 test program, the HF release has remained at a level of 50-150 PPB.



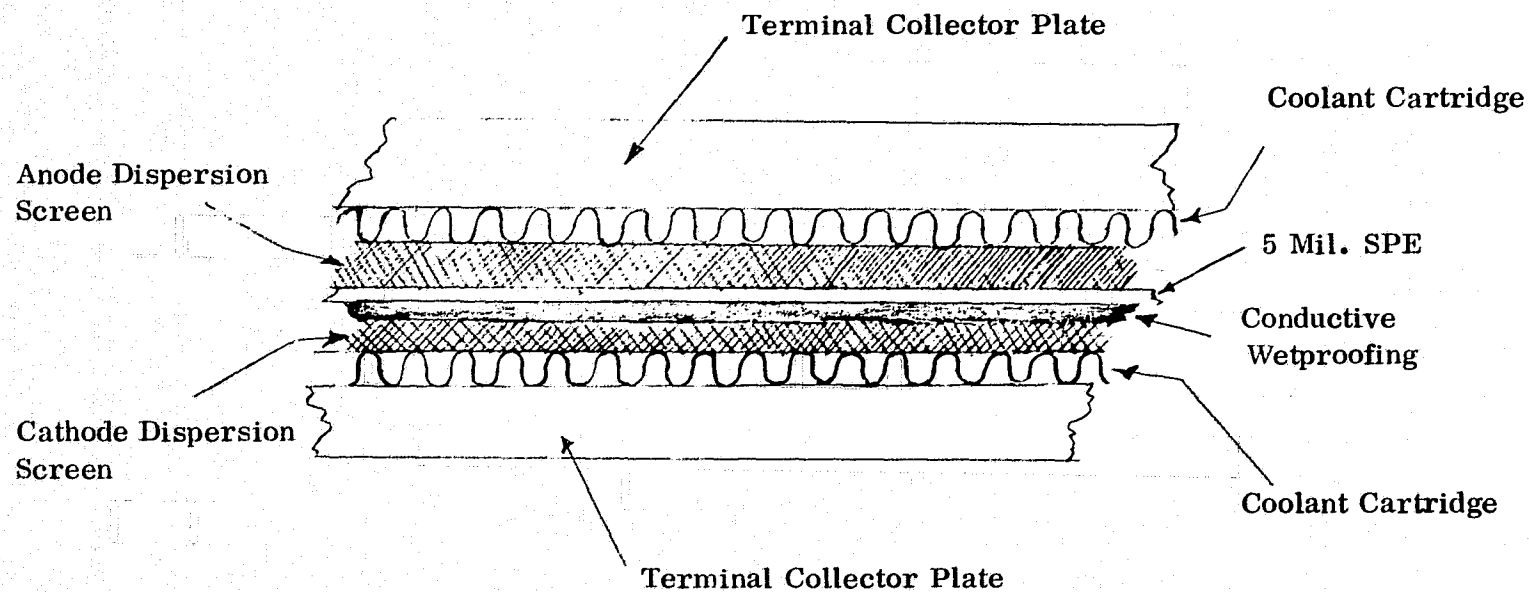


Figure 28. NT-03 Cross Section



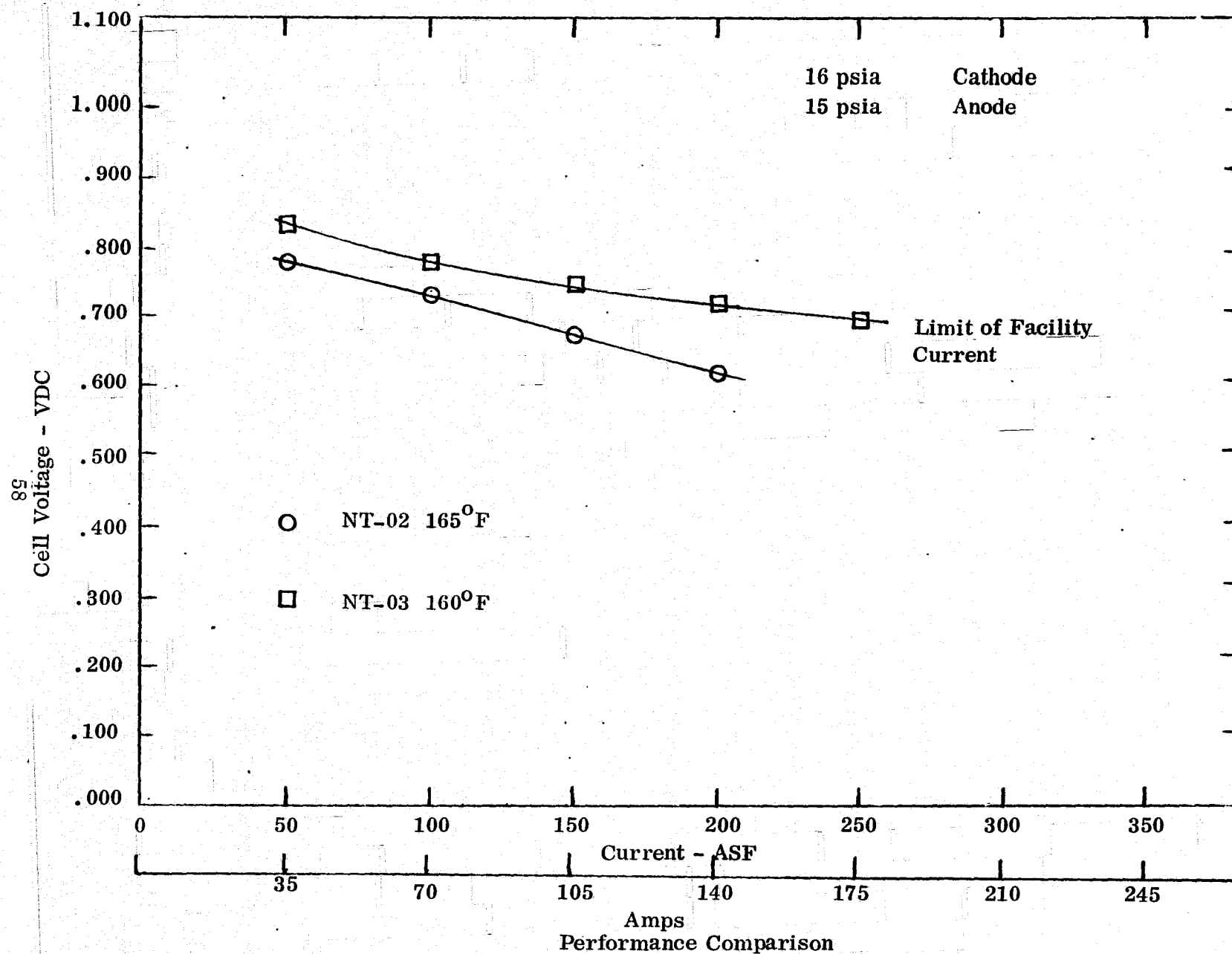


Figure 29.

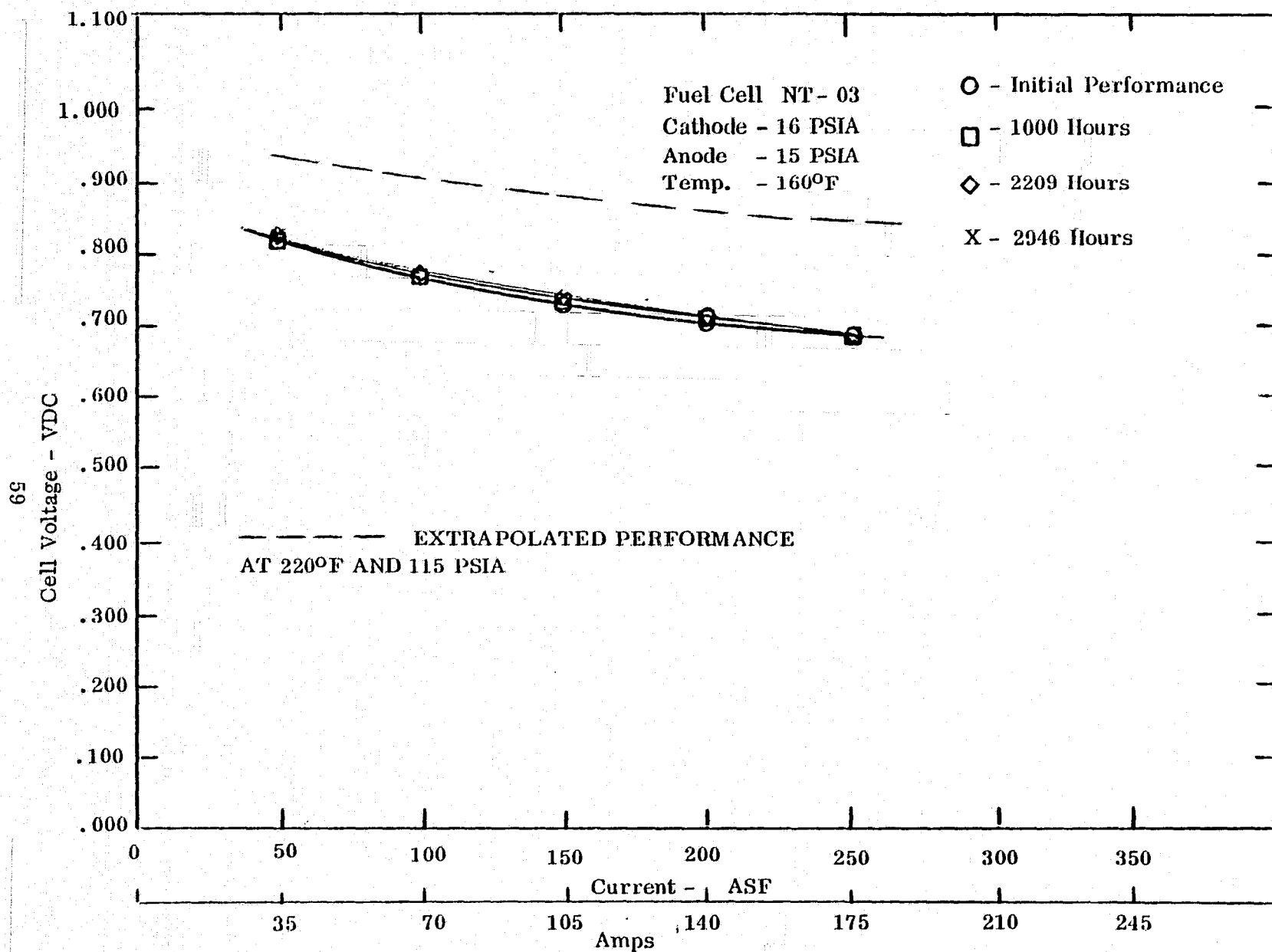


Figure 30. O<sub>2</sub>/H<sub>2</sub> Performance



### 3.3 Systems Study

The purpose of the system study was to evaluate the impact of the various technology advancements on potential future space applications. The areas of study were to include but not be limited to the following:

- Heat rejection requirements
- Specific reactant consumption
- Parasitic power requirements
- System weight analysis
- Cost analysis
- System efficiency
- Power section (fuel cell module) power rating optimization
- Cell size optimization

Initially NASA/JSC submitted the preliminary fuel cell specifications. One for a space station power system (see TableXII) and one for a space tug power system (see TableXIII). During that course of the Phase III Program, two additional potential applications were brought to light. The first was for a second generation space shuttle fuel cell capable of operation on the abundantly available propulsion grade reactants currently on board the space shuttle. The purpose of this would be to increase both mission duration up to 30 days and fuel cell useful life up to the vehicle protected life of 20,000 hours. For the purpose of this study, the original space shuttle fuel cell requirements were assumed except:

- Operation on 125 psia propulsion grade reactants
- Maximum F.C.P. load increase to 14 KW from 12 KW
- Minimum F.C.P. load increased to 4 KW from 2 KW

The second potential new application that was discussed during the Phase III time frame was that of the power platform. The understanding was that this power plant application must be compatible with the space shuttle power system for space link-up missions. For this reason the space shuttle specification was considered with the following exceptions:

- Operation on electrolysis generator reactants.
- Power range of 25 to 250 KW.



TABLE XII  
FUEL CELL SPECIFICATION

SPACE STATION POWER SYSTEM

SOLAR ARRAY/FUEL CELL/ELECTROLYSIS SYSTEM

- POWER: 50-100 KW
  - VOLTAGE: 56-200 VOLTS  
NOMINAL - 112 VOLTS
  - LIFE: 5-10 YEARS WITH MAINTENANCE
  - HEAT REJECTION - SPACE RADIATORS
  - REACTANTS -  $H_2/O_2$  (ELECTROLYSIS PRODUCTS)
  - OPERATIONAL DUTY CYCLE
    - ORBITAL ALTITUDE - 500 KM
    - ORBITAL PERIOD - 94 MINUTES (APPROXIMATELY)
      - LIGHT SIDE - 58 MINUTES
      - DARK SIDE - 36 MINUTES
- (NOTE: FUEL CELL SUPPLIES BUS POWER DURING DARK SIDE OPERATION, S/A SUPPLIES BUS POWER, INCLUDING ELECTROLYSIS POWER, DURING LIGHT SIDE OPERATION. POWER TRANSFER MODE IS CURRENTLY UNDEFINED)
- INTERFACES:
    - FLUID - WATER STORAGE  
REACTANT
    - ELECTRICAL - DISTRIBUTION BUSES
      - INSTRUMENTATION
  - START/STOP CAPABILITY - CAPABILITY FOR AUTOMATIC STARTUP AND SHUTDOWN IN TBD MINUTES
- START AND STOP SHALL NOT CONSTRAIN LIFE EXPECTANCY





TABLE XII (Continued)

- ELECTRICAL POWER REQUIREMENTS - INPUT POWER, TYPE AND QUALITY OF MOTORS, VALVES, HEATERS, ETC. SHALL BE TBD.
- REACTANT PURGING - FLOW RATE, DURATION - TBD.
- PHYSICAL CHARACTERISTICS
  - ENVELOPE - TBD
  - WEIGHT - TBD
  - MOUNTING - TBD



TABLE XIII  
FUEL CELL SPECIFICATION

SPACE TUG POWER SYSTEM

FUEL CELL ELECTRICAL SYSTEM

- POWER - 3 KW
  - GROWTH POTENTIAL - 24KW (3-8 KW MODULES)
- VOLTAGE - 30 VOLTS (NOMINAL)
- LIFE - 5000 HOURS WITH 100 RESTARTS
- HEAT REJECTION - SPACE RADIATORS
- REACTANTS - PROPULSION GRADE  $H_2/O_2$ 
  - LOW PRESSURE - 16 PSIA (NOMINAL)
  - .1% TO .5% HELIUM DILUENT
- INTERFACES
  - FLUID - WATER STORAGE  
REACTANT GASES
  - ELECTRICAL - DISTRIBUTION BUSES  
INSTRUMENTATION
- START/STOP - AUTOMATIC STARTUP AND SHUTDOWN  
CAPABILITY IN TBD MINUTES
- ELECTRICAL POWER REQUIREMENTS - INPUT POWER  
TYPE, QUALITY, ETC., FOR STARTUP, SHUTDOWN,  
PARASITIC COMPONENTS, ETC., SHALL BE TBD
- REACTANT PURGING - FLOW RATE, DURATION, TBD
- PHYSICAL CHARACTERISTICS
  - ENVELOPE - TBD
  - WEIGHT - 15#/KW (MAX)
  - MOUNTING - TBD



A computer model of the fuel cell characteristics was established and was utilized as inputs to the overall system study. Data from Vought Corporation on the space shuttle radiator and Hamilton-Standard on the space shuttle fuel cell heat exchanger also served as inputs to the system analysis.

The thermodynamic model of the fuel cell module was completed and included in a computer subroutine package which was used for a complete electrochemical, thermodynamic and fluid flow analysis of the whole system.

The system study computer outputs established a near optimum cell sizing of 1.1 Ft<sup>2</sup> active area. Utilizing established life conditions of 180°F and 500 ASF, Tables XIV, XV display the characteristics of a 36-cell stack with a 4 to 14 KW rating between 28.00 volts and 32.24 volts. This Space Shuttle-sized hardware is conceived as having 18 cells on either side of a central feed plate with pressurized end plates. (See Figure 31.) In this configuration, the 36 cells would be series connected in order to provide the 28-32.24 volts.

To provide additional power for a power platform at a voltage compatible with Space Shuttle, 36 cells would be provided on either side of the feed plate. In this case, the cells on either side of the central feed plate would be electrically paralleled to provide 25 KW at 28.5 volts. (See Table XVI.)

To provide the 50 KW at approximately 112 volts for Space Station applications, the number of cells would be increased to 72 on either side of the central feed plate, with all 144 cells electrically in series. Table XVII displays the systems characteristics.

To provide the required 8 KW of the space tug vehicle with the propulsion reactants at 16 psia the number of 1.1 Ft<sup>2</sup> cells electrically in series were increased from the space shuttle case from 36 to 43. Table XVIII provides the 8 KW maximum load data and Table XIX provides similar data on the same power plant at 3 KW net output.



TABLE XIV

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SPACE SHUTTLE APPLICATION  
FUEL CELL MODULE CHARACTERISTICS

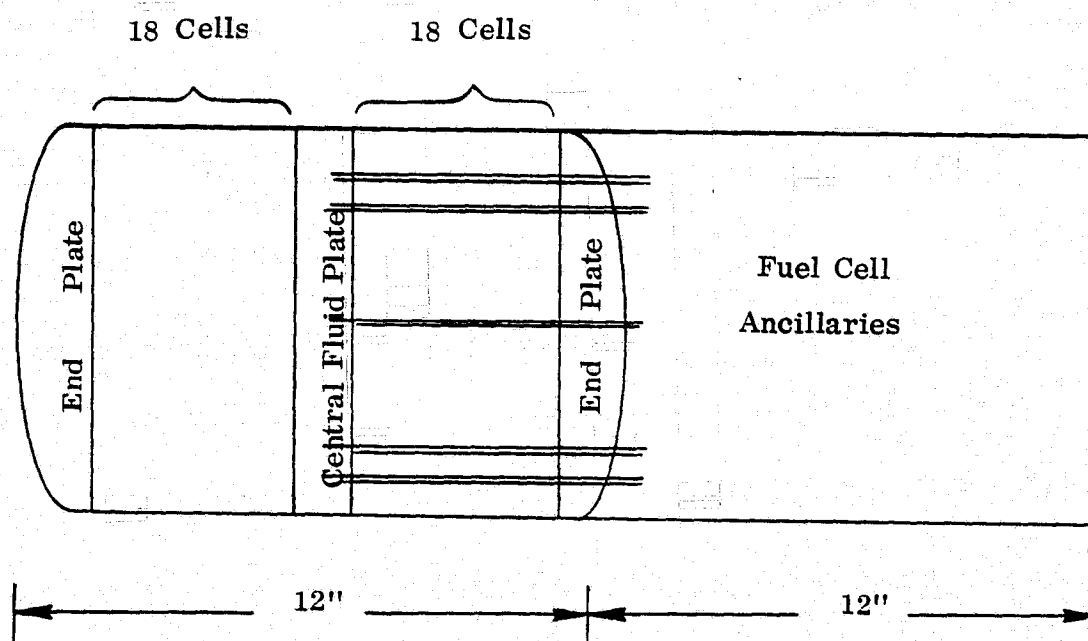
NET POWER OUTPUT	14.000	KW
MODULE POWER OUTPUT	14.206	KW
NO. FUEL CELLS PER STACK	36	
NO. STACKS IN PARALLEL	1	
TOTAL NO. CELLS IN SYSTEM	36	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.7777	VOLTS
ANODE PRESS CORRECTION	.0000	VOLTS
IDEAL CELL VOLTAGE	1.1673	VOLTS
CELL OVERVOLTAGE	.3896	VOLTS
STACK TERMINAL VOLTAGE	28.00	VOLTS
STACK CURRENT	507.4	AMP
SYSTEM CURRENT	507.4	AMP
EFFECTIVE SYSTEM CURRENT	517.8	AMP
CURRENT DENSITY	461.29	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	9.45	AMP/SQ FT
FUEL CELL EFFICIENCY	.5285	
CURRENT EFFICIENCY	.9799	
MODULE EFFICIENCY	.5179	
SYSTEM EFFICIENCY	.5103	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2877	GM/GM SPE
RELATIVE HUMIDITY, H2 SIDE	.9006	
HYDROGEN CONSUMPTION	1.546	LB/HR
OXYGEN CONSUMPTION	12.27	LB/HR
WATER PRODUCTION	13.81	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.1036	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	.88163	LB/HR
VAPOR FLOW RATE(O2 INLET)	.53575	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.13584	LB/HR
VOLTAGE EQUIV HHV	1.4843	VOLTS
MODULE HEAT GENERATION	46247.3	B/HR
MODULE SENSIBLE HEAT LOSS	-279.7	B/HR
HEAT FOR INLET HUMIDIFICATION	1259.5	B/HR
PRODUCT WATER COOLING TO 75F	1518.2	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	3317.5	B/HR
OXYGEN PREHEAT & EVAPORATION	2359.7	B/HR
SYSTEM HEAT REJECTION	39311.1	B/HR
MODULE COOLANT FLOW	4614.3	LB/HR
COOLANT FLOW RATE	9.477	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.72	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	112.0	PSIA
OXYGEN INLET PRESSURE	115.0	PSIA
MODULE INLET TEMP	175.0	DEG F
MODULE OUTLET TEMP	185.0	DEG F
MODULE MEAN TEMP	180.0	DEG F

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TABLE XV

SPACE SHUTTLE APPLICATION  
FUEL CELL MODULE CHARACTERISTICS

NET POWER OUTPUT	4.000	KW
MODULE POWER OUTPUT	4.206	KW
NO.FUEL CELLS PER STACK	36	
NO.STACKS IN PARALLEL	1	
TOTAL NO.CELLS IN SYSTEM	36	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.3957	VOLTS
ANODE PRESS CORRECTION	.0000	VOLTS
IDEAL CELL VOLTAGE	1.2150	VOLTS
CELL OVERVOLTAGE	.3193	VOLTS
STACK TERMINAL VOLTAGE	32.24	VOLTS
STACK CURRENT	130.5	AMP
SYSTEM CURRENT	130.5	AMP
EFFECTIVE SYSTEM CURRENT	142.3	AMP
CURRENT DENSITY	118.59	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	10.76	AMP/SQ FT
FUEL CELL EFFICIENCY	.6085	
CURRENT EFFICIENCY	.9169	
MODULE EFFICIENCY	.5579	
SYSTEM EFFICIENCY	.5306	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2377	GM/GM SPE
RELATIVE HUMIDITY,H2 SIDE	.9803	
HYDROGEN CONSUMPTION	.425	LB/HR
OXYGEN CONSUMPTION	3.37	LB/HR
WATER PRODUCTION	3.80	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.0278	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	.24226	LB/HR
VAPOR FLOW RATE(O2 INLET)	.14721	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.03128	LB/HR
VOLTAGE EQUIV HHV	1.4848	VOLTS
MODULE HEAT GENERATION	11713.5	B/HR
MODULE SENSIBLE HEAT LOSS	-115.4	B/HR
HEAT FOR INLET HUMIDIFICATION	354.8	B/HR
PRODUCT WATER COOLING TO 75F	338.8	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	911.6	B/HR
OXYGEN PREHEAT & EVAPORATION	648.4	B/HR
SYSTEM HEAT REJECTION	9798.7	B/HR
MODULE COOLANT FLOW	4614.8	LB/HR
COOLANT FLOW RATE	9.477	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.72	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	112.0	PSIA
OXYGEN INLET PRESSURE	115.0	PSIA
MODULE INLET TEMP	175.0	DEG F
MODULE OUTLET TEMP	177.5	DEG F
MODULE MEAN TEMP	176.3	DEG F



Cross Section 14" X 14"  
Weight  $\approx$  150 Lbs

Fuel Cell Powerplant  
Space Shuttle Application  
Figure 31

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TABLE XVI

POWER PLATFORM APPLICATION  
FUEL CELL MODULE CHARACTERISTICS

NET POWER OUTPUT	25.000	KW
MODULE POWER OUTPUT	25.351	KW
NO.FUEL CELLS PER STACK	36	
NO.STACKS IN PARALLEL	2	
TOTAL NO.CELLS IN SYSTEM	72	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.7916	VOLTS
ANODE PRESS CORRECTION	.0000	VOLTS
IDEAL CELL VOLTAGE	1.1759	VOLTS
CELL OVERVOLTAGE	.3843	VOLTS
STACK TERMINAL VOLTAGE	28.50	VOLTS
STACK CURRENT	444.8	AMP
SYSTEM CURRENT	889.7	AMP
EFFECTIVE SYSTEM CURRENT	911.0	AMP
CURRENT DENSITY	404.40	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	9.67	AMP/SQ FT
FUEL CELL EFFICIENCY	.5379	
CURRENT EFFICIENCY	.9767	
MODULE EFFICIENCY	.5253	
SYSTEM EFFICIENCY	.5131	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2877	GM/GM SPE
RELATIVE HUMIDITY,H2 SIDE	.9157	
HYDROGEN CONSUMPTION	2.719	LB/HR
OXYGEN CONSUMPTION	21.53	LB/HR
WATER PRODUCTION	24.30	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.1824	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	1.55102	LB/HR
VAPOR FLOW RATE(O2 INLET)	.94253	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.23995	LB/HR
VOLTAGE EQUIV HHV	1.4843	VOLTS
MODULE HEAT GENERATION	80126.7	B/HR
MODULE SENSIBLE HEAT LOSS	-486.3	B/HR
HEAT FOR INLET HUMIDIFICATION	2214.4	B/HR
PRODUCT WATER COOLING TO 75F	2675.2	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	5836.3	B/HR
OXYGEN PREHEAT & EVAPORATION	4151.4	B/HR
SYSTEM HEAT REJECTION	67924.6	B/HR
MODULE COOLANT FLOW	7359.2	LB/HR
COOLANT FLOW RATE	16.140	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.72	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	112.0	PSIA
OXYGEN INLET PRESSURE	115.0	PSIA
MODULE INLET TEMP	175.0	DEG F
MODULE OUTLET TEMP	185.2	DEG F
MODULE MEAN TEMP	180.1	DEG F

TABLE XVII

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SPACE STATION APPLICATION  
FUEL CELL MODULE CHARACTERISTICS

NET POWER OUTPUT	50.000	KW
MODULE POWER OUTPUT	50.704	KW
NO. FUEL CELLS PER STACK	144	
NO. STACKS IN PARALLEL	1	
TOTAL NO. CELLS IN SYSTEM	144	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.7903	VOLTS
ANODE PRESS CORRECTION	.0000	VOLTS
IDEAL CELL VOLTAGE	1.1758	VOLTS
CELL OVERVOLTAGE	.3855	VOLTS
STACK TERMINAL VOLTAGE	113.80	VOLTS
STACK CURRENT	445.6	AMP
SYSTEM CURRENT	445.6	AMP
EFFECTIVE SYSTEM CURRENT	456.2	AMP
CURRENT DENSITY	405.07	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	9.67	AMP/SQ FT
FUEL CELL EFFICIENCY	.5370	
CURRENT EFFICIENCY	.9767	
MODULE EFFICIENCY	.5245	
SYSTEM EFFICIENCY	.5172	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2377	GM/GM SPE
RELATIVE HUMIDITY, H2 SIDE	.9156	
HYDROGEN CONSUMPTION	5.447	LB/HR
OXYGEN CONSUMPTION	43.23	LB/HR
WATER PRODUCTION	48.68	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.3655	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	3.10700	LB/HR
VAPOR FLOW RATE(O2 INLET)	1.88806	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.48064	LB/HR
VOLTAGE EQUIV HHV	1.4848	VOLTS
MODULE HEAT GENERATION	160774.6	B/HR
MODULE SENSIBLE HEAT LOSS	-974.2	B/HR
HEAT FOR INLET HUMIDIFICATION	4435.8	B/HR
PRODUCT WATER COOLING TO 75F	5353.8	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	11691.2	B/HR
OXYGEN PREHEAT & EVAPORATION	8316.0	B/HR
SYSTEM HEAT REJECTION	136331.5	B/HR
MODULE COOLANT FLOW	15772.5	LB/HR
COOLANT FLOW RATE	32.391	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.72	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	112.0	PSIA
OXYGEN INLET PRESSURE	115.0	PSIA
MODULE INLET TEMP	175.0	DEG F
MODULE OUTLET TEMP	185.2	DEG F
MODULE MEAN TEMP	180.1	DEG F



TABLE XVIII

SPACE TUG APPLICATION  
FUEL CELL MODULE CHARACTERISTICS,

NET POWER OUTPUT	8.000	KW
MODULE POWER OUTPUT	8.178	KW
NO. FUEL CELLS PER STACK	43	
NO. STACKS IN PARALLEL	1	
TOTAL NO. CELLS IN SYSTEM	43	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.6524	VOLTS
ANODE PRESS CORRECTION	.1037	VOLTS
IDEAL CELL VOLTAGE	1.1476	VOLTS
CELL OVERVOLTAGE	.4952	VOLTS
STACK TERMINAL VOLTAGE	28.05	VOLTS
STACK CURRENT	291.5	AMP
SYSTEM CURRENT	291.5	AMP
EFFECTIVE SYSTEM CURRENT	292.3	AMP
CURRENT DENSITY	265.01	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	.76	AMP/SQ FT
FUEL CELL EFFICIENCY	.4426	
CURRENT EFFICIENCY	.9971	
MODULE EFFICIENCY	.4414	
SYSTEM EFFICIENCY	.4318	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2377	GM/GM SPE
RELATIVE HUMIDITY, H2 SIDE	.9341	
HYDROGEN CONSUMPTION	1.042	LB/HR
OXYGEN CONSUMPTION	8.27	LB/HR
WATER PRODUCTION	9.31	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.6365	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	3.73623	LB/HR
VAPOR FLOW RATE(O2 INLET)	1.76453	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.49112	LB/HR
VOLTAGE EQUIV HHV	1.4848	VOLTS
MODULE HEAT GENERATION	40213.6	B/HR
MODULE SENSIBLE HEAT LOSS	-4435.0	B/HR
HEAT FOR INLET HUMIDIFICATION	4998.4	B/HR
PRODUCT WATER COOLING TO 75F	790.8	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	2147.4	B/HR
OXYGEN PREHEAT & EVAPORATION	1545.3	B/HR
SYSTEM HEAT REJECTION	31527.5	B/HR
MODULE COOLANT FLOW	4017.5	LB/HR
COOLANT FLOW RATE	8.184	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.53	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	13.0	PSIA
OXYGEN INLET PRESSURE	16.0	PSIA
MODULE INLET TEMP	150.0	DEG F
MODULE OUTLET TEMP	160.0	DEG F
MODULE MEAN TEMP	155.0	DEG F

TABLE XIX

ORIGINAL PAGE 15  
OF POOR QUALITY

# SPACE TUG APPLICATION

## FUEL CELL MODULE CHARACTERISTICS

NET POWER OUTPUT	3.000	KW
MODULE POWER OUTPUT	3.173	KW
NO. FUEL CELLS PER STACK	43	
NO. STACKS IN PARALLEL	1	
TOTAL NO. CELLS IN SYSTEM	43	
CELL ACTIVE AREA	1.1000	SQ FT
CELL VOLTAGE	.7662	VOLTS
ANODE PRESS CORRECTION	.0910	VOLTS
IDEAL CELL VOLTAGE	1.1752	VOLTS
CELL OVERVOLTAGE	.4090	VOLTS
STACK TERMINAL VOLTAGE	32.95	VOLTS
STACK CURRENT	96.5	AMP
SYSTEM CURRENT	96.5	AMP
EFFECTIVE SYSTEM CURRENT	97.4	AMP
CURRENT DENSITY	87.69	AMP/SQ FT
PERMEABILITY LOSS(EQUIV)	.84	AMP/SQ FT
FUEL CELL EFFICIENCY	.5193	
CURRENT EFFICIENCY	.9905	
MODULE EFFICIENCY	.5148	
SYSTEM EFFICIENCY	.4860	
SPE THICKNESS	.005	IN.
SPE EQUILIBRATION TEMPERATURE	212	DEG F
IEC(ION EXCHANGE COEFFICIENT)	.825	MEQ/GM
SPE WATER CONTENT	.2877	GM/GM SPE
RELATIVE HUMIDITY, H2 SIDE	.9320	
HYDROGEN CONSUMPTION	.347	LB/HR
OXYGEN CONSUMPTION	2.76	LB/HR
WATER PRODUCTION	3.10	LB/HR
OXYGEN RECIRCULATION(FRACTION)	.25	
OXYGEN RECIRCULATION RATE	.1966	CU FT/MIN
VAPOR FLOW RATE(H2 INLET)	1.24459	LB/HR
VAPOR FLOW RATE(O2 INLET)	.58731	LB/HR
VAPOR FLOW RATE(O2 OUTLET)	.12945	LB/HR
VOLTAGE EQUIV HHV	1.4848	VOLTS
MODULE HEAT GENERATION	11918.3	B/HR
MODULE SENSIBLE HEAT LOSS	-1546.9	B/HR
HEAT FOR INLET HUMIDIFICATION	1711.6	B/HR
PRODUCT WATER COOLING TO 75F	241.6	B/HR
SAT LIQ HYDROGEN AT 34 PSIA AND OXYGEN AT 22 PSIA		
HYDROGEN PREHEAT & EVAPORATION	715.3	B/HR
OXYGEN PREHEAT & EVAPORATION	514.3	B/HR
SYSTEM HEAT REJECTION	8976.6	B/HR
MODULE COOLANT FLOW	4017.5	LB/HR
COOLANT FLOW RATE	8.184	GPM
COOLANT PUMP DIFF PRESS	10.0	PSID
COOLANT PUMP HEAD	23.53	FT
COOLANT PUMP EFFICIENCY	.200	
HYDROGEN INLET PRESSURE	13.0	PSIA
OXYGEN INLET PRESSURE	16.0	PSIA
MODULE INLET TEMP	150.0	DEG F
MODULE OUTLET TEMP	153.0	DEG F
MODULE MEAN TEMP	151.5	DEG F

#### 4.0 CONCLUSIONS

The conclusions realized during this Phase III Technology Program can be summarized by the following statements:

- With the improved understanding of operational mechanisms, the potential for development of a high performance SPE fuel cell remains a relatively low risk.
- Noble metal loading in the SPE fuel cell catalyst is not a practical cost effective endeavor for space type fuel cells. Cost and weight of noble metal has become somewhat insignificant with base line loadings at high current densities.
- Continued low level investigations of alternate electrolytes should be continued for the potential for increased performance. As in the case of catalyst reductions, the cost of electrolytes for space hardware at high current density has become insignificant. Alternate electrolytes are not technically ready for scale-up.
- The mechanism(s) of improved performance through air activation is not fully understood and requires additional evaluation. All system study results were based on demonstrated performance without air activation.
- Significant life capability of the conductive wetproofing configuration has been demonstrated via the life testing of 0.7 Ft<sup>2</sup> cell NT-03. This configuration is suitable and ready for flight weight configuration scale-up.
- The open gap cathode configuration is quite prone to damage from facility type failures that result in pressure reversals. The scale-up hardware with conductive wetproofing will be designed with pressure reversal capability.
- Preliminary results from the system studies have verified significant positive impact on space power systems characteristics.



## 5.0 RECOMMENDATIONS

It is the recommendation of GE/DECP that the Solid Polymer Electrolyte Fuel Cell Technology Program be continued through Phase V. At the end of Phase V the suitability of the advanced SPE Fuel Cell Technology for future space applications will be established. The Phase IV Program, which is currently in progress, and the proposed Phase V Program are summarized in the following paragraphs.

### 5.1 Phase IV Program

The program for the Phase IV technology advancement activities includes continued laboratory endurance testing of 3 x 3 cells, initial regenerative fuel cell evaluations in 3 x 3 hardware, full scale cell and stack design, and single cell unit fabrication and evaluation. Figure 32 displays the schedule of the technical efforts in Phase IV.

#### 5.1.1 Task 1.0 - Endurance Evaluations

During Phase III, a series of endurance tests were started on 3 x 3 laboratory-sized cells. The primary purpose of these cell tests is to confirm the inherent long life/stable performance of the Solid Polymer Electrolyte fuel cell at temperatures, pressures and current densities above previously demonstrated.

These tests are continuing into Phase IV to establish sufficient hours of operation so as to confirm the desired cell operational characteristics.

#### 5.1.2 Task 2.0 - Regenerative Lab Evaluations

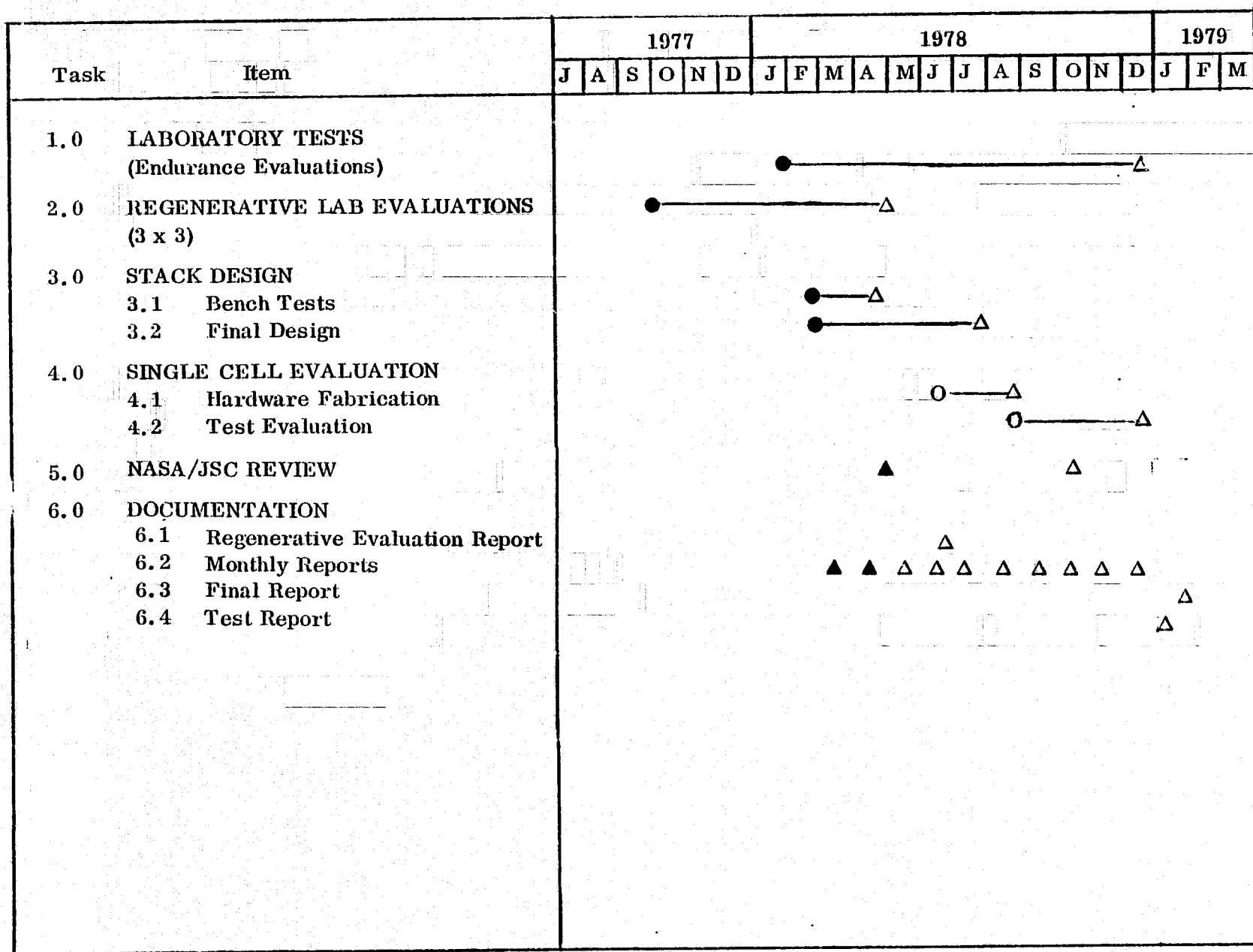
This task provides the ground work for future space energy storage systems and is timed for completion in mid 1978. It is expected that any efforts carried on after that point in time will be covered under separate contract.

In this task, facilities will be modified incorporating the capability of operating 3 x 3 cells in either the fuel cell or electrolysis mode. Cell(s) will be fabricated and test evaluated. The configuration of the cells will be a modified fuel cell baseline incorporating either E-50 or E-5 catalyst on the oxygen producing electrode. The test evaluations will include:

- Fuel cell performance with E-50/E-5 on anode and/or cathode.
- Electrolysis with O<sub>2</sub> water feed on wetproofed side.
- Electrolysis with O<sub>2</sub> water feed reversing mode (i. e., O<sub>2</sub> becomes H<sub>2</sub> side when switching modes).



## Milestone Chart



\* Contract Modification #2



- H<sub>2</sub> side water feed.

#### 5.1.3 Task 3.0 - Stack Design

This task is made up of two sub-tasks. The first being bench testing of configuration concepts and the second being the actual design effort.

##### 5.1.3.1 Sub-task 3.1 - Bench Tests

Utilizing inputs from the Phase III system study, bench test will be performed on various component concepts. These bench tests will include:

- Flow tests of the various subsystem configurations.
- Cell and chamber sealing techniques.
- Electrical conductivity tests.

##### 5.1.3.2 Sub-task 3.2 - Final Design

This sub-task will include the design of the individual cell of a space configuration and the support equipment such as end plates and tie rods. The end plates will not be of a flight configuration in that they will not include internal reactant humidifiers. The end plates will provide appropriate compression of the cell components and provide internal manifolding of the required system fluids.

#### 5.1.4 Task 4.0 - Single Cell Evaluation

This task is divided into two sub-tasks. One sub-task is the fabrication of a single cell unit and the second sub-task concerns facility preparations and test evaluation of the single cell unit.

##### 5.1.4.1 Sub-task 4.1 - Hardware Fabrication

In this sub-task the single cell hardware with appropriate end plates, terminal plates etc., will be fabricated and be subjected to non-operational check-out tests. Tests to be performed include:

- Leakage tests
- Flow tests
- Electrical tests.

##### 5.1.4.2 Sub-task 4.2 - Test Evaluation

Existing DECP facilities will be modified to provide the capability of operating the hardware produced in sub-task 4.1. The facilities will include provisions for reactant prehumidification and unattended operation. These facilities will be checked out prior to use with the single cell stack.



The single cell stack will be activated and operated at various temperatures, pressures and current densities to allow direct performance comparison to the 3 x 3 cell data. Following the collection of parametric data, endurance testing will be performed on the unit.

## 5.2 Phase V - Proposed Program

The proposed program for the Phase V technology advancement activities includes continued laboratory testing of 3 x 3 cells, full-scale small stack and reactor design, and small stack and reactor stack fabrications and evaluations. Figure 33 displays the schedule of the individual Phase V tasks. Details of the proposed program are as follows:

### 5.2.1 Task 1.0 - Laboratory Tests

The purpose of this task is to continue the endurance tests of laboratory 3 x 3 life tests which are in progress to establish additional confidence in the conductive wetproofing configuration. New endurance cells will be evaluated as deemed important to the overall program success. Design modifications that appear appropriate for the full-scale hardware will undergo checkout on the laboratory-scale 3 x 3 test hardware.

### 5.2.2 Task 2.0 Single Cell Evaluation

This task includes the continuation of parametric and endurance testing of the single cell hardware which was designed, fabricated, and initially tested under Phase IV of the technology program. Modifications to this hardware may be incorporated for evaluation prior to incorporation into higher levels of stacks.

### 5.2.3 Task 3.0 - Small Stack Evaluation

This task is divided into two sub-tasks. One sub-task is the fabrication of a small stack, and the second sub-task concerns facility preparations and test evaluation of the small stack.

#### 5.2.3.1 Sub-task 3.1 - Hardware Fabrication

In this sub-task a four-cell stack with appropriate non-flight end plates, terminal plates etc., will be fabricated and be subjected to non-operational check-out tests. Tests to be performed include:

- Leakage tests
- Flow tests
- Electrical tests



# NASA/JSC SOLID POLYMER ELECTROLYTE FUEL CELL TECHNOLOGY PROGRAM

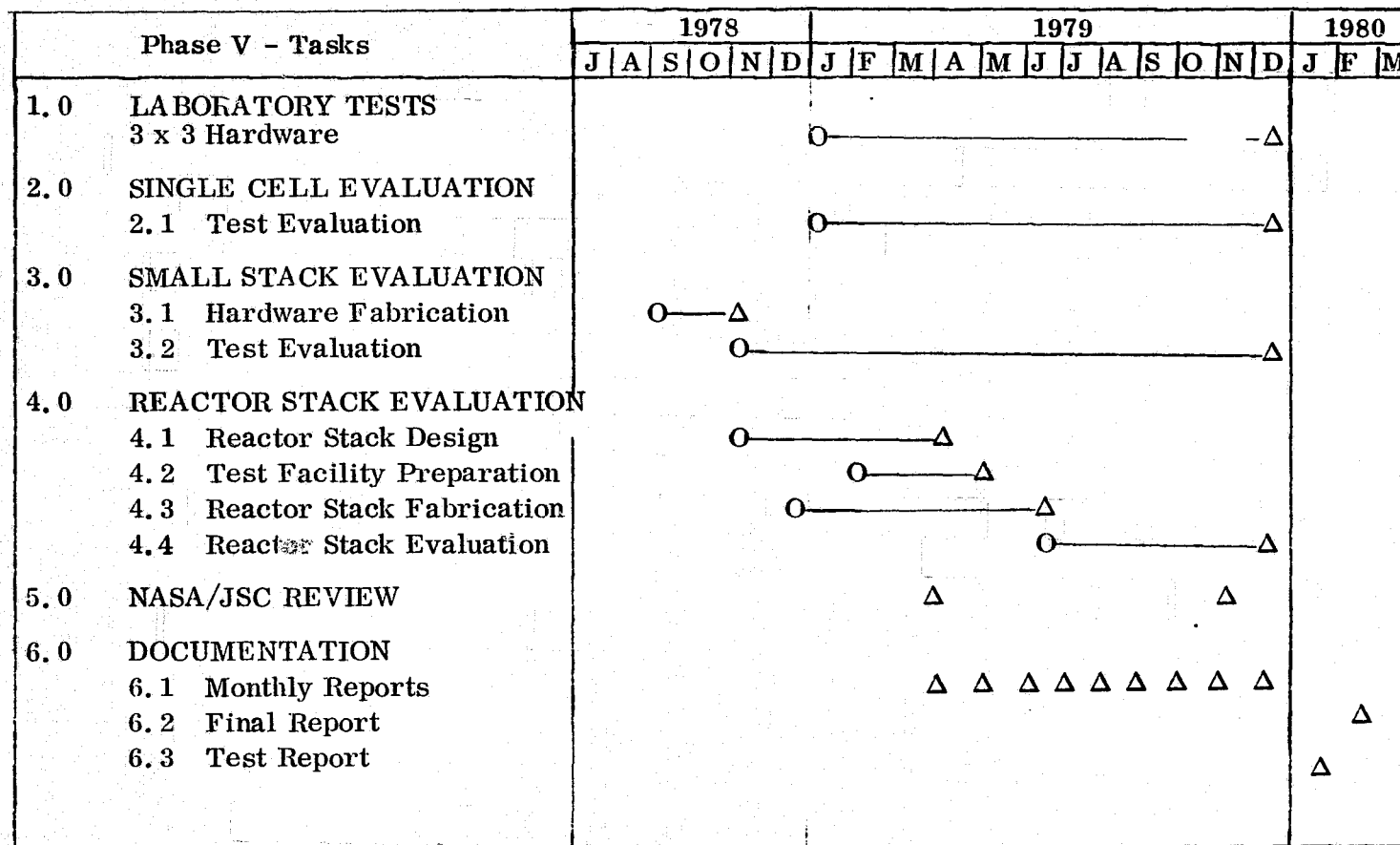


Figure 33.





The active area and configuration of the individual cells will be of the type developed under the single cell evaluation tasks of Phases IV and V. The preliminary sizing of this hardware includes an active area of 1.1 Ft<sup>2</sup> for each cell. The individual fuel cell assembly will consist of a membrane and electrode assembly and fluid separator assembly. The membrane will be approximately .005 inch thick Nafion<sup>®</sup> film with platinum electrodes pressed into each side. Noble metal loading on each electrode will be at a level of 4 grams/ft<sup>2</sup>. A conductive wetproofing film will be attached to the cathode electrode to facilitate water removal and current collection. An uncatalyzed portion of the membrane will extend to the outer frame edge and around the fluid manifold ports of the fluid separator assembly. This extended membrane provides the gasket seal both around the perimeter and around the fluid manifolds within the cells and compressed between end plates.

The fluid separator assembly is a welded niobium assembly which provides flow paths for coolant, oxygen, hydrogen and product water. The coolant cavity is supported by a niobium truss. The two plates are embossed with a flow pattern for the hydrogen, oxygen and product water flow which is supplemented with an expanded niobium screen in both reactant cavities.

The dry weight of the individual cell assembly will be approximately 1.5 pounds. Total cell weight with coolant will be approximately 1.9 pounds.

The end plates for this four-cell stack will be of the boiler plate type with all attendant functional aspects; however, no attempt will be made to optimize for weight and volume.

#### 5.2.3.2 Sub-task 3.2 - Test Evaluation

Existing DECP facilities will be modified to provide the capability of operating the hardware produced in sub-task 3.1. The facilities will include provisions for reactant prehumidification and unattended operation. These facilities will be checked out prior to use with the four-cell stack.

The four-cell stack will be activated and operated at various temperatures, pressures and current densities to allow direct performance comparison to the 3 x 3 cell data. Endurance testing will be performed on the unit following the collection of parametric data.

Preliminary set of conditions for the endurance testing is as follows:

- Current density            100 - 500 ASF
- Pressure                    115 psia
- Temperature                175 - 185°F



The preliminary conditions are within the range of the demonstrated 40,000 hour life and were selected for that primary reason. As 3 x 3 test results indicate endurance capabilities at more optimum conditions, these will be factored into the test plan. Even at these somewhat conservative operating conditions, a power output of nearly 400 watts per cell will be generated. The wet cell weight (not including end plates or ancillaries) will be approximately 4.8 pounds/KW.

#### 5.2.4 Task 4.0 Reactor Stack Design

This task is divided into four sub-tasks with the overall objective of demonstrating a multi-KW stack.

##### 5.2.4.1 Reactor Stack Design

The three major stack components for the reactor stack include:

- Cell assemblies
- End plate
- Central fluid plate (reactant humidifier)

The cell assembly design for the multi-KW reactor stack will be established in the evaluations of the single cell hardware and the four-cell stack hardware. In the single cell design task of Phase IV, the cell integral manifold porting will have been sized to accommodate the flow of as many as 72 cells on either side of the central fluid plate.

The end plate design will be completed as part of this sub-task. The basic concepts to be utilized for this end plate will be related to the end plates developed for the Navy Aircraft Oxygen Generation Stack (NOBOGS). This end plate utilized a pressurized chamber which applied a sealing and active area force on the cells at approximately 75 psi above maximum operating pressure (i.e., approximately 400 psi).

The central fluid plate with built-in reactant humidifiers will also be designed as part of this sub-task. The concepts utilized will be a combination of previously successful designs (i.e., the common feed plate of NOBOGS, and the end plate reactant humidifier of the NASA/JSC technology program for space shuttles).

##### 5.2.4.2 Sub-task 4.2 - Test Facility Preparation

Test facilities will be prepared for the unattended operation of the multi-KW reactor stack. The major facility functions will include:

- Pressure, temperature and flow controls for oxidant, fuel and coolant.



- Variable load bank.
- Continuous recording of temperatures.
- Continuous recording of voltage and current.
- Controls for steady-state automatic operation with safety shutdowns.

The facility will undergo a complete checkout prior to installation of the reactor stack. These checks will include:

- Subsystem leakage checks.
- Flow and pressure control checks.
- Electrical subsystem operation and checkout.

#### 5.2.4.3 Sub-task 4.3 - Reactor Stack Fabrication

The reactor stack as presently conceived could include up to 18-cell assemblies, one flight weight pressurization end plate, and a central fluid plate. A built-in reactant humidifier will also be incorporated if practical within the scope of the program. A boiler plate end plate will substitute for the "second half" of the reactor stack. This arrangement allows full-sized reactor stack fluid flow evaluations with the economy of requiring only half a stack. (See Figure 34).

Complete checkout of the end plate and central fluid plates will be performed before integration with the cell assemblies. These checks will include:

- Pressure tests
- Flow and leakage tests
- Humidification tests

The assembled reactor stack will then undergo leakage and electrical checks. Electrical checks will include shunting and internal resistance measurements.

#### 5.2.4.4 Sub-task 4.4 - Reactor Stack Evaluation

The fuel cell reactor stack will be installed in the facility. Flow, leakage and electrical checks of the facility/stack integration will be performed. Once these checkouts are successfully completed, the reactor stack will be activated and a series of parametric tests performed.

The reactor stack will be subjected to an endurance run following the parametric testing. 2000 hours of endurance testing will be the goal of the reactor stack operation.



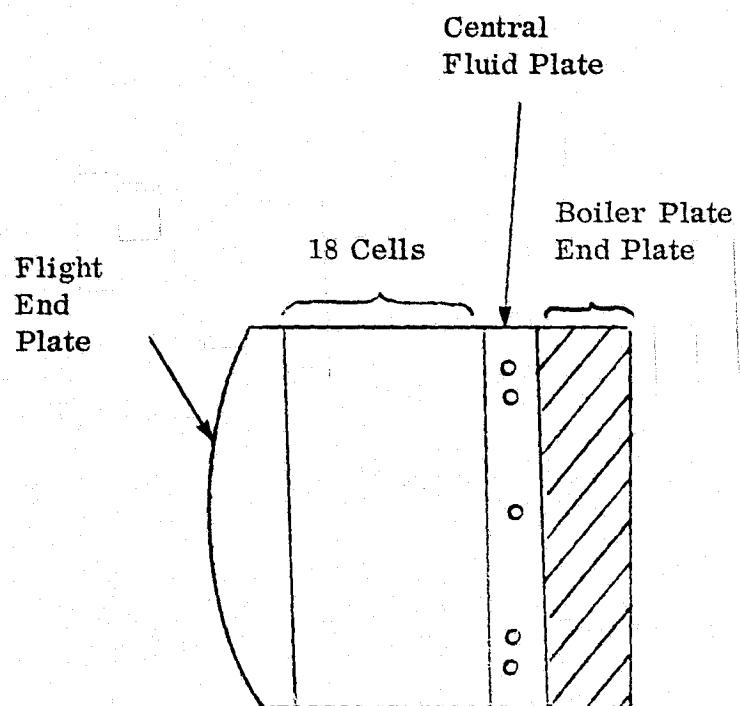


Figure 34. Reactor Stack Assembly